IRE Transactions

ON RELIABILITY AND QUALITY CONTROL

Volume RQC-10 August, 1961 Number 2

TABLE OF CONTENTS

PUBLISHED BY THE
PROFESSIONAL GROUP ON RELIABILITY AND QUALITY CONTROL

IRE PROFESSIONAL GROUP ON RELIABILITY AND QUALITY CONTROL

The Professional Group on Reliability and Quality Control is an organization, within the framework of the IRE, of members with principal professional interest in Reliability and Quality Control. All members of the IRE are eligible for membership in the Group and will receive all Group publications upon payment of prescribed fees.

Annual Fee: $3.00

IRE TRANSACTIONS ®

on Reliability and Quality Control

Editor
W. X. Lamb, Jr.

Published by The Institute of Radio Engineers, Inc., for the Professional Group on Reliability and Quality Control, 1 East 79 Street, New York 21, N. Y. Responsibility for the contents rests upon the authors, and not upon the IRE, the Group or its members. Individual copies of this issue and all available back issues may be purchased at the following prices: IRE members (one copy) $2.25, libraries and colleges $3.25, all others $4.50. Yearly subscription rate: non-members $17.00; libraries and colleges $12.75.

Reliability in Missile and Space Operations*

MAJ. GEN. LEIGHTON I. DAVIS†

Mr. Chairman, distinguished guests—I am honored and pleased to be asked to participate in this Seventh Annual Symposium on Reliability. From a study of the abstracts of the papers submitted and discussed these past two days it is obvious that there is great interest in the subject, and the success of this meeting is evidence of the great progress that has been made in organizing discussions of the great progress.

At the Air Force Missile Test Center—the executive agent for the Defense Department for the operation of the Atlantic Missile Range—we sit at the other end of the road. We are not interested in the organization of discussions on reliability—we are interested in reliability—period. At the research and development test range, we are at the end of the road in the progression from planning—to design—to fabrication—to preflight test—to launch. We are interested in results. Those that we have seen so far in development tests show we are climbing the reliability growth curve. We still have a ways to go to achieve the levels we need to put a human into space and return him safely. Unreliability can mean a very expensive missile and space program for this country.

To supply background I will describe the Atlantic missile Range, show some pictures of missile and spacecraft launchings, talk a little about the important role of component research and development, then attempt to prove my point by giving some abbreviated statistics on success and failure in our missile and space research and development programs.

[Briefing on the AFMTC (Cape Canaveral and Atlantic Missile Range) and missile test procedures followed.]

These films are very interesting. I hope they kept you awake; if not I'll dub in sound next time—the sound of hundreds of thousands of pounds of rocket thrust on take-off—something you'll never forget if you witness a large booster struggle to push its load off the stand and out into space.

Speaking of "struggling" to lift a load off the stand, let's take a look at some quantitative measures of our progress in our "struggle" to achieve reliable missiles and space systems.

The Atlantic Missile Range was 10 years old this last year—in that decade almost 1000 missiles have been launched—from small weather rockets to huge ballistic birds. There is a great deal of information to be gained by analysis of the results of these flights. However, this is a research and development range. In fact, there have been almost as many different models of missiles tested as launches of one type of missile. Any attempt to form judgments from the data available must take cognizance of the small samples of data, and the numerous engineering changes made on each type as it is tested.

With that bow to the statistician, we must couple the statement attributed to Lord Kelvin: "If you can't measure (assign a number to) a thing, you don't know much about it."

The data I present pertain to the boosters (rocket engines) used for satellite and space operations. For several reasons, including security, these figures should not be used as a measure of our military operational readiness. For example, most of the boosters are highly instrumented research and development birds. Only performance as it relates to a first-stage mission has been considered. With these qualifications let's look at four slides showing the growth of reliability for the boosters used in our space programs. This includes the performance of the booster or first stage of missile flight. Launches are scored as either successes or failures according to whether the rocket engine and guidance system operated for the programmed time. Failure to attain desired thrust and velocity is considered a failure. Each launch is weighted serially, thereby discounting early experience and weighting heavily the immediate past. The value associated with each launch is a measure of probability of success on the next launch.

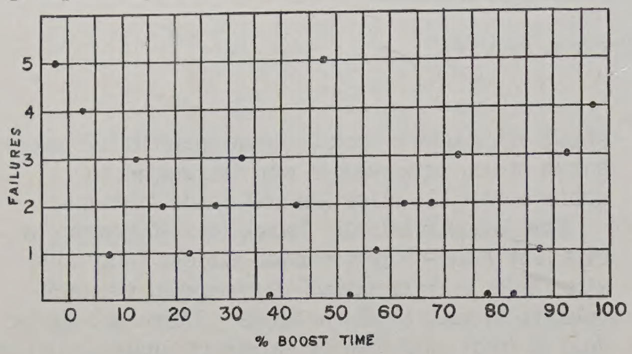
[Slide 4 (Booster "X"), Slide 5 (Booster "Y"), Slide 6 (last 50 launches, Booster "Y"), and Slide 7 (Booster "Z") followed.]

These slides are indicative of our success in achieving reliability—the subject of this symposium. They are quantative—and that too has

*Address given before the Seventh Natl. Symp. on Reliability and Quality Control, Philadelphia, Pa., January 10, 1961.

†Commander, AF Missile Test Center, Cape Canaveral, Fla., and Atlantic Missile Range.

been emphasized in your proceedings—quantitative specifications of reliability of components and quantitative budgets of reliability within the subgroups of systems.



Slide 8—Failure vs per cent boost time.

In Slide 8 we have a composite of 44 failures in some 200 launchings of missiles and first-stage boosters. These data are arranged to study the relation between the time of failure and the boost period. Failures were grouped in five per cent increments of total burning time. As you see, we experienced five failures before lift-off, four failures in the first five per cent of the boost period, one failure in the next five per cent, three in the next, and so on.

It was hoped that a study of this type would reveal a possibility of separating early failures—infant-mortality type—from random failures, and "wear out failures." As a first approximation, one could write an expression relating probability of failure to per cent of burning time, postulating a term independent of time, one inversely related to time and a third proportional to time. After plotting the data, I did not even bother to attempt to fit such a function to the data. It seems obvious that our failures are pretty randomly distributed throughout the powered flight phase.

In looking at this plot, I am reminded of the physicist who said—and I probably misquote: "It is sometimes more fruitful to ponder on the obvious than to belabor the obscure."

In this case, it is obvious that there is no strong correlation between probability of failure and the shock of starting—or to the accumulation of strain as the acceleration builds up in the latter part of the boost period—or correlation to staging which occurs roughly at about 40 per cent of the burn time for ATLAS—or to high "q" loading that occurs roughly at this point—or to thermal effects that might increase the incidence of failures at the end of the powered flights.

I am inclined to think we must look to some other factor, other than design weakness, for a cause and effect relationship.

In addition to design weaknesses, we have component part unreliability and human errors as causes of missile failures.

Most of this meeting has been devoted to discussions of component reliability. I have noticed the phrases "product improvement," "production lot sampling," and "field test engineers" and wondered about their applicability to the relatively few missiles actually fired in the development of modern weapon systems.

The statistical methods used in sampling millions of rounds of ammunition and thousands of vacuum tubes and transistors seem far removed from the problem of putting a Tiros in orbit on the first or second attempt. As for the field test engineer, I haven't got a job description for the man who might service a Midas on location, so to speak.

However these methods and discussions are not irrelevant to the missile and space problem. As a matter of fact, we won't achieve the success we need unless we redouble our efforts, and double our expenditures, on achieving orders of magnitude improvement in parts reliability.

Great strides have been made in the past two years in the missile program: the BMD 58-10 exhibits specifying quantitative measures of reliability to be placed in contracts—the IDEP (Interdepartmental Data Exchange Program) agreement set-up by General Ritland, BMD; General Funk, AMC; Admiral Raborn, Bureau of Ordnance; and General Barkley, US Army—is evidence of the strong interservice cooperation on the subject of reliability.

The third class of cause of failure is human error.

The final operational reliability is a composite of many things:

a) Quality of component parts.
b) Careful design.
c) Competent fabrication and assembly.
d) Comprehensive system engineering to insure compatibility of the whole weapon system—ground support—all in operational mode.
e) Intelligent design of preflight checks.
f) Inspection and discipline in preflight operations.

Notice that in the listing of the parts of the problem, I have used words such as: "careful, competent, comprehensive, intelligent, inspection and discipline." It is obvious that these words pertain to human attributes not to the characteristics of inanimate objects. They emphasize the dominant role the individual plays in missile reliability, whether it be design, fabrication, preflight adjustment, or inspection.

Perhaps in pondering on the significance of Slide 8 (attempting to relate the probability of failure to some physical phenomena at a unique time in the boost), we are overlooking the obvious —that people are involved in all the operations on the missile. Their mistakes would not result in failures at any particular phase of powered flight.

In our fascination over the statistics on parts and assemblies, let us not forget the role that people play. We won't have acceptable missile performance or an efficient space program unless it is conducted by intelligent, trained, experienced people with an appreciation of the discipline required to achieve that last 10 per cent in reliability.

The figures I have given may seem to paint a black picture of our missile and space program. If so, I have presented them in the wrong light.

We are making progress, and I am proud of our achievements. There is no reason to go around in sack cloth and ashes—to say that because the USSR has bigger engines that they are ahead of us in the "space race."

Look at our present position. When I last checked, this afternoon, there were 17 satellites orbiting the earth. That doesn't count space garbage—boosters, after bodies, and so forth. Sixteen of these satellites were launched by the United States. The lone Soviet satellite is silent—dead. Of the 16 United States birds, seven or eight are transmitting signals.

The 4 lunar-space probes are not supplying data—two U.S.-launched and two USSR-launched (one, of course, hit the moon). Pioneer V was still transmitting when we lost contact—some 27 million miles from home.

I said seven or eight satellites are still transmitting. We have a problem because these things can be too reliable; we don't want to accumulate a flock of birds circling the earth forever, fouling up the frequency bands. I don't know the exact number because I understand one is being turned off on command to clear the frequency.

To me, seven or eight satellites in orbit, furnishing weather data, navigation data, data on the environment in near space, is very significant.

We are ahead of the Soviets in the exploration and peaceful use of space. The key to success in space operations is reliability and the understanding of the subject that comes out of meetings like this will keep us ahead in the race.

Thank you for your kind attention.

Reliability—Whose Responsibility?*

H. LESLIE HOFFMAN†, Senior Member, IRE

I wish to thank Mr. Kuehn and his program committee for the opportunity of making the keynote address before the Seventh National Symposium on Reliability and Quality Control. I wish also to extend my congratulations to all the Symposium committees for the manner in which they organized the conference. The large attendance reflects this effort as well as the depth of interest in reliability and quality control by many segments of many industries.

I interpret my invitation as being rather unique. I was asked to speak about the AGREE reliability program at Hoffman Electronics. I assume the program committee thought you would be interested in learning particularly about our problems and successes in applying AGREE procedures and standards to building the complex airborne portion of TACAN. I must also assume that you will want to know about the impressions and conclusions we have gained from this pioneering experience.

It may interest you to know that there was a certain amount of irony involved in our applying AGREE procedures for the first time in the electronics industry. At the time I was President of EIA, in 1955, the term "reliability" was being used widely, but with little understanding. It meant many different things to many different people. We needed both a quantitative and qualitative means of defining and measuring reliability in a given equipment.

In characteristic association style, I appointed a committee made up of experts in the industry and the services to make a study of reliability for electronic equipment. The outgrowth of its work was the AGREE Report. Jim Bridges and his people in the Defense Department were the first to recognize the benefits that could be derived from a concentrated drive on reliability and gave substantial support to the industry's activity.

Although I had something to do with starting the ball rolling on the AGREE concept as we know it today, the role of guinea pig for the program was not one we actively sought. It all started with the Air Force requesting a transfer of the procurement authority from the Navy to the Air Force for their TACAN requirements. This request was given a thorough analysis by both services and the Defense Department. It was pointed out by the Navy that they had established substantial procedures and facilities to insure the reliability of this equipment. They had accumulated considerable data and knowledge regarding the reliability of TACAN and they were concerned that in its transfer to the Air Force there would be no way of monitoring the reliability of the redesigned equipment. Meanwhile, the procurement was being processed by the Air Force. Subsequently, the Defense Department recommended that AGREE reliability procedures be incorporated in the proposed contract; first, because of the data accumulated by the Navy, it would be a good test case for AGREE, and second, it was insurance for the Air Force getting reliable TACAN equipment.

The AGREE Procedures were then added to the contract requirements. At the time, this action was considered primarily a good resolution of a rather sticky technical interservice problem. Few recognized it as the initiation of a major and brand new method of procurement.

When we bid the job, our people were cognizant of the 75 to 136 hours between failures on the TACAN equipment established by the Navy tests at Johnsville and verified by field tests in Alaska. Consequently, the 150-hour-Mean-Time-Between-Failure required by AGREE did not appear too formidable. Unfortunately, we were unable to evaluate the effect of the additional environmental requirements placed upon the equipment by the AGREE procedures. Nowhere in industry was there reference material upon which to make such an evaluation. We gambled more than we knew on the unknown and, consequently, grossly underestimated the magnitude of the job to be done.

Prior to the present contract three manufacturers, including Hoffman, had built 25,000 of these equipments. The equipment had established a good reputation both for performance and reliability, although the basic performance specifications had never been met completely. Certainly by this time, it was reasoned, we should know how

---

*Address given before the Seventh Natl. Symp. on Reliability and Quality Control, Philadelphia, Pa., January 9, 1961.

†Hoffman Electronics Corp., Los Angeles, Calif.

to build quality into an airborne TACAN equipment and have it give reliable performance, and the magnitude of the upgraded reliability did not seem excessive.

Time did not permit checking out our current equipment against AGREE reliability and procedures prior to the submission of our bid. It was a considerable shock to us to find out later that the equipment that had been built for over seven years had an MTBF of only 17 hours, on the basis of AGREE, and our target was 150 hours: the severity of the AGREE environmental stresses becomes quite apparent when these figures are compared with the rating by Johnsville of 75 to 126 hours on the same equipment.

It is my hope that, even though most of you are competitors, none of you are involved in meeting AGREE specifications with the pressures that existed on this contract. It seemed as if the situation dictated that we do every thing the hard way.

Please do not interpret my remarks as containing bitterness against the procuring services. Why should I blame the customer? The Air Force faced the same problem we did; namely, a lack of data and experience to evaluate the magnitude and effect of the AGREE procedures. The service people knew they wanted more reliable equipment and they hoped that AGREE specification would give it to them.

I think you would be interested to know some of the requirements of this contract:

1) Eliminate some 15 waivers that were applied to previous equipments under the old contract.
2) Improve equipment sensitivity and spectrum. This meant changing the front end from 42 crystals to 126. Reduce the weight, which we did by a factor of 25 per cent. Raise the operational environment from 50,000 feet at half power to 70,000 feet at full power, without pressurization.
3) Make all of these modifications within the same physical configuration of the original equipment so that whenever possible, the new modules or books would be interchangeable, physically and electrically, with the old modules.
4) Take the basic design and incorporate it in a different configuration for B-58's, T-38's and F-104's.
5) Meet AGREE specifications for 150 hours MTBF. As I have previously indicated, this was nearly a nine-fold improvement.

To further compound the difficulties, we were to produce the equipment at a price lower than the previous contracts and begin deliveries nine months after the award.

Only an extreme optimist would claim that this task could be done in the time and cost allowed, and others would read into the above requirements a note of commercial suicide.

In order to prevent you from assuming I had lost my wits completely by actively soliciting such a contract—and with a fair amount of pride—I hasten to report that all of the objectives cited have been met, although with a moderate delay in the shipping schedule. I must admit that in accomplishing these objectives, we invested more of the company's money than I had contemplated. We now have a substantial investment in our Reliability knowhow.

The impact on our people was significant. A tough job requires a level of performance from individuals and organizations over and above the norm. It is a great screening process. So it was with us. We found where our real strength existed, both in people and procedures.

The TACAN-AGREE program forced a complete realignment of our internal procedures. While we were supposed to be working on a production contract, circumstances required us to simultaneously combine research and development with production. In addition, these twin efforts made us realign our concepts regarding both our procedures and relationship with our suppliers.

The heart of AGREE reliability procedure is fundamentally an accelerated test of both components and end-equipment under extreme environmental conditions, coupled with a precisely organized remedial action program indicated by the mathematical interpretation of the test results.

Starting with components, our first task was to determine their reliability in the equipment. This was done by taking our own field reports on the performance of the airborne TACAN and analyzing the component failures. We then secured data from our suppliers. Our next step was to project these against the TR-1100 Curves. The objective of this composite analysis was to establish the reference failure rate per 1000 hours for each component category in terms of both present experience and the achievable reliability level.

The equipment contains 1015 electrical components classified into 10 major categories. To illustrate our problem, let me use vacuum tubes as an example. Previous history indicated an average failure rate for vacuum tubes of 25 per cent per 1000 hours. This rate had to be reduced to less than 3.8 per cent per 1000 hours to meet the AGREE reliability requirements—and there are 58 dual-type tubes in this equipment. Saying it another way, we needed to reduce the number of

tube failures over the entire equipment lifetime of 2000 hours from 29 to 4.

It is interesting to note that we unintentionally inherited a job of educating some of our suppliers on how to test their components for reliability. I would like to pay tribute at this point to the wonderful cooperation we received from most of the components industry. In spite of this fact, it was necessary for us to change approximately 85 per cent of our suppliers. This is not a reflection on the level of parts reliability in the components industry. The component suppliers were meeting the existing military specification. But, these specifications were written before the AGREE procedures and were not adequate for components or equipments being tested under the AGREE stresses.

It is significant that the Darnell Report, aimed at establishing comprehensive component specifications to meet the AGREE reliability levels, was released last May and is now being cussed and discussed by the industry. Our reliability director advises me that this report has considerable merit but does not go far enough on stress levels. From a timing viewpoint, our contract will be completed and very stringent stress levels will have been met well in advance of the time adequate component specifications are established at an industry level.

Fortunately, the Air Force project engineers, in the early phases of the contract, became aware of the complexity of this job. Regular coordination meetings were held to jointly work out the problems as they developed.

I must point out to you that the technical people, in most instances, were much more sympathetic than the contracts people. This is understandable because one group understood the complexity of the problems and the time needed to solve it, while the other had a different slant based on contract costs and schedules.

Solving the problems, however, required a close coordination and the utmost in teamwork among our suppliers, the Hoffman people and our customer. Without it, we wouldn't be talking about a success story today.

Fortunately, our company was large enough to withstand the impact of a program such as this, and yet small enough to keep the lines of communication short. Top management was tied directly into each major problem to not only facilitate decision making but to establish policies and procedures so that responsibilities could be implemented and delegated. In that way, our major energies could be devoted to solving the day-to-day problems within general programs and policies previously established.

Throughout the course of this contract we had many interesting revelations. For instance, only 19 per cent of components in the ARN-21C accounted for 81 per cent of its failures. It is significant to note that the lowest failure rate occurred in components that had been in production for some time. Special components required to improve equipment performance, and which had a low level of production experience, gave us the maximum failure rate.

It was necessary, therefore, to develop new inferential test methods. As an example, in addition to the usual electrical and environmental test given potted components, we weighed them to make certain they had their proper amount of potting compound.

We had instance after instance when it was necessary for our people to convince our suppliers that their established practices were not adequate to insure top level components, and this was not always a pleasant affair.

The task in our own plant was formidable—to meet the requirement of no more than 2 workmanship failures out of 123,000 operations—which means that in assembling the 1015 electrical parts (including 58 tubes and 56 semiconductors) and over 5000 mechanical components, we are allowed one workmanship mistake per 10 completed equipments. This required a substantial upgrading of our own workmanship.

Early in our production period, we started new and intensive training classes for our line workers. Even the screening techniques for new employees were modified. It is interesting, and perhaps significant, to note that only one in twenty job applicants passed the screening test that we established. By the same token, it was necessary to transfer some of our regular employees to less critical jobs. Even some of our supervisors who could not completely face up to the problems realistically were placed elsewhere.

So far, I hope I have been able to give you some feeling for our TACAN-AGREE experience. My comments are necessarily aimed at the management and policy level. The technical details of our program are to be covered in another session by Dr. A. L. Floyd, director of reliability for our company, and one who did a yeoman's job in accomplishing the results that we obtained. Mr. Griffith Lindsay, I am advised, will also participate in this meeting and recount the Air Force's analysis of its experiences. Lindsay is another important member of the manufacturer-supplier-customer team and was most helpful to us in working out the day-to-day problems.

I have outlined the historical background of our experience, commented on some of the peculiar problems involved in the building of airborne TACAN according to AGREE procedures, and

touched on some of the major problems we encountered.

This has been a significant experience to us and, I think, not only adds to the sum total of our knowledge but can be of equal value to the industry if it is utilized. From this viewpoint, I would like to outline some of our observations, conclusions and definition of responsibilities.

1) The AGREE reliability procedure based on pretesting of components and end-equipment is effective for upgrading the reliability of electronic equipment.

2) Reliability costs money initially, but it will reduce the total cost of the equipment and its usage to the Government. As a matter of fact, in this particular contract on 10,000 equipments, we were advised by the Air Force that the savings on maintenance and supply exceeds $125 million, without any credit being given for the decreased aborted missions. I must add, we have had difficulty convincing the Air Force that they should share some of these savings with us.

3) The application of the AGREE procedure must be varied—based on the quantities of equipment involved, as well as the past experience on the particular equipment.

4) Reliability is a growth process in which there is no substitute for experience. Reliability can only be obtained by doing. It is the maturity of design after rugged testing, preproduction and production experience.

5) Reliability must first be designed into equipment, then quality workmanship built into it. Inspection and testing are only verification procedures. The design people should give full consideration to the producibility, maintainability and reliability of both components and end-equipments. They should recognize that this is their responsibility and that production cannot correct improper design. I would quickly add that design should not be blamed for poor workmanship. Consequently, it is the function of testing and quality assurance to not only verify design capabilities, but to monitor workmanship in components and end-equipment as well.

6) Any manufacturer who is considering a contract containing AGREE reliability requirements must critically examine his procedures and his personnel. Both must be capable of meeting a very special kind of challenge. He will also find than an effective in-plant education program will have to be developed to achieve these objectives.

7) A clarification of Defense Department policies regarding reliability specifications on an overall basis is badly needed. At the present time, only the Air Force has indicated its intention of applying AGREE procedures on a broad front. This lack of uniformity of reliability requirements among the three major services is resulting in increased costs and considerable confusion, in both the component manufacturers' and the end-equipment manufacturers' plants. We need, and need badly, a national reliability policy applicable to all types of military electronic equipment and comprehensive enough to not only include the component specifications, but to recognize the operational use of the end-equipment.

8) This reliability policy, once established and initiated with all services, must be supported and recognized by the contracting officers at the point of the original bid.

9) The Defense Department should also establish an equitable policy regarding the expensive environmental test equipment required by component supplier and end-equipment manufacturer to meet the AGREE reliability procedures. At the present time, this is being financed on a project-by-project basis, but many inequalities are developing from this approach. Many competent manufacturers will be excluded as qualified suppliers if they are not included in certain of the favored reliability projects now in existence.

Our own experience was gained on a fixed-price contract, with no such consideration. Other manufacturers are on a CPFF contract, and with full consideration. This is equity?

Perhaps the Defense Department should consider government-owned environmental test facilities in key geographical areas that are available equally to all parts of the industry.

10) Finally, the factor of the extra time required for processing the AGREE procedures should be taken into consideration at the time the original delivery rate is established.

My title is "Reliability—Whose Responsibility?" and I think by this time I should get around to answering the question directly, if I have not already done so indirectly.

In my opinion, the leadership for establishing a higher level of reliability in military electronic equipment should come from the Defense Department in a combined program with the services. They are the customers of industry, and in our country the customer is king. And no matter how severe the requirements, industry somehow always finds a way to meet them if it knows what the customer wants and if he is willing to pay for it.

The joint program developed by industry and the Defense Department, and identified as AGREE, has considerable merit, as our experience indicates. DOD must now decide where and how to apply it and resolve the various technical, contractual and organizational problems with the individual services.

Today we are concerned more than ever with the high cost of military equipment. If our experience of saving $125 million on a $40 million contract can serve as an index, what would be the saving on $10 billion in procurement?

And, dollars are not the prime consideration.

This should be a real incentive to the DOD and the Armed Services. The next step is to establish an incentive for industry rather than trying to force the program through directive.

These, then, are my observations on AGREE reliability and my conclusions, except for one. We, at Hoffman, are somewhat like the college freshman who has just completed the fraternity hazing and has survived. We think it's a fine idea and more people should have the experience, but we are certainly happy that we have it behind us.

Seriously, we always enjoy the challenge of trying something new, and this particular experience has added much to our knowledge of our people and by our people. We feel that we are much better qualified, after this experience, to build sophisticated military electronic equipment with a high degree of reliability for our customers in the years ahead, and I would predict that anyone else taking on such an assignment will end up with the same conclusion.

Do Present Government Procurement Practices Promote Delivery of Unreliable Equipment?*

The Panel

C. M. Ryerson (Chairman)	Chairman of the Board, 7th National Symposium
W. A. MacDonald (Moderator)	Chairman of the Board, Hazeltine Corporation
Capt. J. M. Malloy	Chairman, Armed Services Procurement Regulation Committee, Office of the Assistant Secretary of Defense (Supply and Logistics)
E. V. Huggins	Chairman of the Executive Committee and Vice President, Westinghouse Electric Corporation
W. W. Watts	Group Executive Vice President, Radio Corporation of America

Questioners Group

Maj. Gen. W. A. Davis	USAF, Commanding General AMC Aero Systems Center
RADM L. D. Coates	USN, Director, Naval Development and Planning
Brig. Gen. C. S. Hays	Commanding General U. S. Army Signal Supply Agency
RADM C. F. Horne	USN (Ret.), Vice President and General Manager, Convair
M. E. Jones	Assistant Director Procurement ONM

FOREWORD

This round table discussion was established in the belief that much of the problem of unreliability stems from inadequate communication of concepts and understanding between the top people in military and industry. Open discussion of the common problems should be beneficial to the common cause.

This compilation is a follow-up action to record for further study and discussion the major points brought out at the meeting. Comments from the reader and suggestions on how to make progress in the problem areas described will be appreciated.

C. M. RYERSON
President and Technical Director
Ryerson Associates Inc.
West Collingswood, N. J.

*Proceedings of a round table discussion held at the Seventh Natl. Symp. on Reliability and Quality Control, Philadelphia, Pa., January 9, 1961.

INTRODUCTORY COMMENTS

W. A. MACDONALD

I think we all recognize that the subject we are about to discuss is highly controversial. In recognition of this, I am going to propound the following question:

Do present procurement practices actually promote the delivery of unreliable equipment to the government?

We are particularly concerned with electronic and electromechanical apparatus and systems that are specially developed, designed, and manufactured to satisfy highly specialized needs as differentiated from shelf items or standard articles of trade. Hence, our discussion is intended to revolve around this highly technological class of weapons system. The procedure we propose to pursue here is as follows.

Initially, we had planned that Mr. Bannerman of the Contract Division of the Department of Defense would discuss briefly facts relating to present procurement practices, policies, and procedures applied to government contracts. Unfortunately, Mr. Bannerman is ill in the hospital; however, I am happy that Capt. John M. Malloy, Chairman, Armed Services Procurement Regulations Committee, has undertaken this chore. He will be followed by discussions by the panelists who will consider selected areas of the problem.

In the past few years, innumerable papers, technical, mathematical, and otherwise, have been written, and much work has been done on the subject of reliability and quality control. In spite of the fact that substantial progress has been made in improving the reliability and quality of selected components, there is a very large question as to whether systems reliability is any better, if as good, today as it was some years ago, simply because systems complexity has increased at a much more rapid rate than component reliability.

One might infer from the current technical literature that the right brand of statistical quality control during manufacture will insure reliability. From a practical point of view, nothing could be further from the fact. There are many more important factors which include:

1) Does the initial design philosophy permit adequate factors of safety?
2) Have the manufacturer's past record, experience, and capabilities been adequately considered?
3) Do the contract negotiators ignore useful life cost in order to make a good showing on initial costs?
4) Does the contract timing cycle permit thorough prototype testing and rework?
5) Does the contract authorize product improvement effort?
6) Does the contract vehicle provide for the above and other considerations?

During the past months, great emphasis has been placed on the growing cost of defense needs. I can give you two examples expressed by eminent authorities:

General Trudeau at the NSIA Annual Luncheon: "I challenge you, our industrial leaders, to provide the defense we need on a sound but more economical basis. Present costs are excessive and everyone knows it. We are literally pricing ourselves out of having the capability to defend ourselves adequately."

General Anderson at Dayton (NSIA): "I ask top management to assume the leadership in improving their purchasing organization. I request that they publish detailed policies and procedures in regard to their purchasing systems. I request that particular improvement be made in the two areas of 1) intracompany contracting and 2) in the area of subcontracting with outside firms."

Broadly speaking, I find little to disagree with in these statements except in one area, and this is that a unilateral challenge has been issued to industry to accomplish a desired result when, in point of fact, it should be a bilateral team effort. Fortunately, I see a growing awareness by many in developing better mutual understandings between the user and producer. The quoted statements may not fully recognize that the current rules and regulations under which industry has been required to operate are so rigid that if these same rules are continued, we will continue to have either

1) increasing prices and moderate quality, or
2) lower initial prices and unsatisfactory quality.

Reliability must be designed and built into equipment and cannot be accomplished solely by inspection and quality control during manufacture. Inherently, in this class of custom designed apparatus, a reliable piece of equipment costs more to produce than a shoddy piece of merchandise. Therefore, bidding on an advertised or competitive basis with award to the bidder with lowest initial price without a common yardstick for measuring the degree of reliability being procured, inherently precludes such a contract procedure from providing highly reliable equipment.

At the other extreme, let us consider the situation of a noncompetitive contract award with a blank check attached where reliability considerations are allowed to be one of the controlling factors. In such a case, in time, anyone can produce

reliability but what also will happen is late delivery of equipment or fantastically excessive costs, or both.

The two extremes enumerated result in situations which can and do happen continually under our present contract structure.

I believe it is about time we approach the problem of

1) operational requirements,
2) reliability,
3) useful life costs,

from a simple practical, bilateral business point of view and, most important, as a joint team effort between the customer and supplier. If such an approach is employed, I am convinced that the objective of high reliability can be achieved and that all of our necessary weapons systems can be procured and maintained within an over-all budget certainly no greater and probably less than we have been accustomed to in the past.

PROCUREMENT IN THE DEPARTMENT OF DEFENSE

CAPT. JOHN M. MALLOY, SC, USN

I have been asked by your Chairman to set the stage for our discussion by briefly discussing some background information on Defense procurement, particularly as to the types of contracts that are in general use. I hope that this background will be helpful in our consideration of the business aspects of reliability.

As you are aware, our Board of Directors—the Congress—has a good deal to say about how we conduct our buying operations. Congress has spoken out directly through passage of the Armed Services Procurement Act. This piece of legislation indicates the basic intent and policy of the Congress. They want us to purchase by means of formal advertising whenever feasible and practicable. This, of course, means that our requirements, including reliability levels, must be set down in explicit fashion so as to allow full and free competition. Awards are made on the basis of these required quality levels on a price basis, without further discussion.

This then, is our starting point. Fortunately, the Congress recognized that the bulk of our complicated military weapons could not fit this rather rigid pattern. If you don't purchase by formal advertising, you must use what we know as negotiation. Here again, however, the Congress has indicated to us in numerous ways that they intend that we secure the maximum practicable competition. We ourselves would pursue this objective even if the Congressional hot-foot were not present.

It seems rather obvious that competitors must stand on an equal footing. To accomplish this result, we must come forward with a clear statement of our needs. We have very little difficulty in defending or justifying our legitimate quality requirements. It is axiomatic, however, that whatever our requirements as to quality and reliability may be, they must be capable of being stated with precision and there must be an objective method of measuring compliance. This is, of course, often a difficult problem. The point I wish to stress here is that we hear all kinds of suggestions for strange contracting techniques which are designed to overcome the inherent difficulty of stating and measuring our reliability requirements. Our contracting officers are motivated to buy reliable products as much as any other segment of our organization. I suspect that many of you have found, however, that our purchase people are not very tolerant of "loose as a goose" deals to compensate for a problem that is difficult for others to solve.

There are a variety of contract types used in the Department of Defense, running from cost reimbursement types to several kinds of flexible fixed-price types. The firm fixed-price contract has wide usage, and under the right conditions, is the preferred type of contract. It is the usual form of contract in formally advertised procurements. As its name implies, this type of contract is an agreement by the contractor to furnish supplies or services at a specified price which is not subject to adjustment in the light of performance costs. It carries the greatest risk and offers the greatest possibility of profit of any type of contract. This type of contract is best suited for procurements where reasonably definite specifications are available, production experience is present and costs can be predicted with reasonable certainty. It is the easiest and least costly of all contract types to administer. Thirty-eight per cent of our contract dollars (8 billion) were placed on this type of contract.

Another form of fixed-price type contract is one which provides for the redetermination of price. We have various types of redeterminable contracts and they are usually used when a firm fixed-price cannot be established at the outset. What is needed in this situation, therefore, is a form of contract whereby the parties, in the light of the actual cost experience gained during a partial production of the contract items, can take a second look at the reasonableness of the price initially negotiated. About 5 per cent of our dollars (1.3 billion) were applied to this type of contract.

Another type of flexible price contract is the fixed-price incentive contract. This type of

contract provides for the initial negotiation of a target cost, a target profit, a ceiling price and a final profit formula which allows the contractor to participate (usually in the range of 10 per cent to 20 per cent in any savings resulting from his bettering of the target cost). Its objective is to give the contractor a built-in incentive to reduce his cost of performance since his profit is increased thereby. This type of contract is used primarily on large contracts where there is a sufficiently long period of performance to permit achievement of substantial cost reductions. We spent 13-1/2 per cent of our dollars (3 billion) under this type of contract.

The cost-plus-a-fixed-fee contract is the most important cost-reimbursement-type contract. In addition to the payment of a fixed fee to the contractor, this type of contract provides for reimbursement of the allowable cost of performing the contract. It is used primarily where the scope and nature of the work cannot be definitely specified, as, for example, in the research and development area. This type of contract obviously provides minimum incentive for cost reductions. Because of this lack of incentive, the cost-plus-a-fixed-fee contract is the contract type we least prefer. We use it not because of preference, but because of necessity. This least favored type of contract has been used during the past fiscal year in contracts obligating more dollars than were obligated by any of the various fixed-price type of contracts. This reflects and emphasizes the fact that, regardless of preference, contract usage is dictated by the procurement situation. The fact that the trend in dollars obligated by cost-plus-a-fixed-fee contracts has been constantly increasing clearly evidences the trend in defense contracting, where development of new weapons prodominates, and buys of production quantities of weapons for inventory become less common. During the past fiscal year, 42.6 per cent of our contract dollars (9 billion) were placed under cost-reimbursement-type contracts. The cost-plus-incentive-fee contract is a variation of the cost-plus-a-fixed-fee contract and is designed to provide the same type of incentive for cost reduction as is inherent in the fixed-price incentive contract, which I described earlier.

We use two types of special incentive contracts which should be of particular interest to this group. The first of these is called a performance-incentive-type contract. Its purpose is to provide an incentive to the contract to surpass stated goals of performance, by providing for increases in the fee or profit to the extent that such goals are surpassed, and for decreases to the extent that such targets are not met. Performance includes timeliness of delivery, capability and serviceability of the product, ease and simplicity of operation, economy of maintenance, etc. Performance that is the minimum which the Government will accept is mandatory under the terms of the contract and is not subject to the incentive feature, but must be accomplished within the established basic price limitation. Thus, the incentive feature is applied to desired performance rather than mandatory performance; to performance goals rather than performance requirements. For example, performance goals might relate to the speed of an aircraft or ship, thrust of an engine, fuel economy, or levels of reliability. This type of contract is usually used in connection with a fixed-price incentive contract, although it can be used in connection with a cost-plus-incentive-fee contract. This type of contract does not have wide usage today, but we are finding more and more areas where its application is feasible.

The second type of special incentive contract is one which contains the concept of value engineering incentives. This type of incentive is suitable primarily where items being procured are covered by firm specifications. Value engineering incentives are designed to encourage the contractor to maintain a staff devoting time and effort to value engineering studies to reduce costs under the contract. In return for this effort, the contractor receives a stated percentage of the resultant savings. The value engineering study is an intensive appraisal of all of the elements of the design, manufacture or construction, inspection, installation and maintenance of an item and its components, including the applicable specifications and operational requirements, in order to achieve necessary performance, maintainability, and reliability at minimum cost.

These, then, are but a few of the tools available to our contracting people. We do not feel that there are any basic missing links in our purchasing procedures with respect to our ability to contract for reliable equipment. In actual practice, we are faced with the stark reality of not always being able to act in the most optimum way. This same problem is faced continually in day-to-day decisions in the business world. There is always the necessity of trading off such factors as cost, reliability, delivery times, quality levels, maintenance and so forth. There are rarely any pat answers or automatic solutions in our business.

COST AND RELIABILITY

W. A. MACDONALD

I want to speak to you briefly on some of the

simple relationships between cost and reliability. Considering first the very broad subject of costs, the Fiscal year 1959 budget for all electronics expenditures was \$5.935 billion. This is broken down into three broad areas comprising

Production Procurement	\$4.175 billion
Operations and Maintenance	0.890
R&D Test and Evaluation	0.870
TOTAL	\$5.935 billion.

For the major item "Production Procurement" (\$4.175 billion) to be meaningful, it must be further broken down.

The general procurement pattern for new equipment that has been followed for some time and is certainly true from Hazeltine's experience is

Product development and prototype costs	10 per cent
Support equipment costs	30 per cent
Spare parts costs	30 per cent
TOTAL	70 per cent.

This means that only 30 per cent of our Production Procurement fund of \$4.175 billion or \$1.25 billion goes into new weapons hardware. The remainder of our production procurement fund of \$2.92 billion plus \$0.890 for operation and maintenance and, probably, half of the \$0.870 billion or \$0.435 billion allocated to test and evaluation results in a grand total of \$4.245 billion required to satisfy the four passive functions of:

a) Product development and prototype test
b) Operations and maintenance
c) Support equipment
d) Spares.

If we assume that the useful life of our electronic equipment is 5 to 5-1/2 years without modernization, and the buildup in the weapons system in previous years was of the same general order of magnitude as in 1959, then our electronic weapons systems inventory must have a useful investment value of about \$7 billion. To maintain this inventory costs \$4.245 billion, or 60 per cent of its initial cost each year it is in operation.

Now, to give us some reference point as to just what the above figures mean, let us take two illustrative examples. Recognizing that the cases are not precisely the same, let us nevertheless first consider home entertainment receivers and television receivers and their maintenance costs. Although the figures vary materially from company to company, evidence indicates that yearly maintenance costs are reasonably uniform over the life of the apparatus and vary from a minimum of 5 per cent per year to a maximum of 10 per cent to 15 per cent.

In the automotive industry, conditions are slightly different, with some companies guaranteeing their product for the first 12- to 18-month period at a minimum maintenance cost of about 3 per cent, which may gradually rise to 10 per cent over the life of the machine.

With ratios varying from 6 to 20 times greater for the maintenance of military electronic equipment, one must inescapably conclude that there is something badly out of balance in the relationship between the initial or instantaneous costs and useful life costs of the equipment and systems presently under procurement.

In an effort to improve reliability and quality of systems hardware, DOD directive 3222.1 was issued July 5, 1956. Its purpose was to provide a slow, orderly, and systematic series of steps between the creation of a new apparatus or system and its final production. As a means of improving reliability, there is little doubt that it has great merit. Unfortunately, it can delay production of the equipment from 2 to 5 years.

In conclusion, I should like to refer to my opening remarks and more particularly to the substance of General Trudeau's NSIA luncheon comments.

> "I challenge you, our industrial leaders, to provide the defense we need on a sound but more economical basis. Present costs are excessive and everyone knows it. We are literally pricing ourselves out of having the capability to defend ourselves adequately."

I agree with General Trudeau wholeheartedly.

We are pricing ourselves out of business, not because of excessive systems hardware cost, but because of excessive maintenance costs. We have gone far beyond a safe balance in reducing the initial or instantaneous apparatus and system costs and are paying a terrible direct price for maintenance over the useful life of the apparatus.

PROCUREMENT PRACTICES AND RELIABILITY

E. V. HUGGINS

Against the analysis by Capt. Malloy of the various types and forms of procurement and procurement contracts which are available to the military services and to the industry supplying it, it is not possible in a short time to handle in detail the broad question which has been posed to this panel. An additional question might be raised as to the extent to which the actual practice follows the contract forms and regulations, but that again can't be answered here. However, the analysis of costs in the maintenance area provided by Mr. MacDonald certainly justifies a broad look at concepts which underlie the practices and

perhaps permit the suggestion of a concept which in the minds of many of us is too little used.

Basically, defense procurement now consists of first, the purchase of equipment and second, its maintenance and support, each separated in its own sphere but each having a distinct relationship, but not usually correlated, to total ultimate cost of the operation of the equipment over its estimated useful life. Would it not be better, in many cases, to combine these steps into the single procurement of a function?

Let me illustrate with an example from commercial business: when a builder of a large office building purchases elevators, he is not buying elevators as pieces of equipment. What he wants, and the only thing that he wants, is the function of vertical transportation. Without the availability and capability of that function at all times the function of the entire building fails. So what does he do—he buys not only the elevators and their installation, but also buys the maintenance of the elevators to assure their functioning on a long-term basis. Normally, and particularly this is true with the complex, modern, high-speed electronically automated elevators, he buys all of these from the manufacturer of the equipment.

What does this mean from the building owner's standpoint? It means that he is looking at the total cost of the function, including the price of the equipment, the price of its installation and the price of its maintenance. In other words, how much does he have to pay to get the building's subsystem, the vertical transportation function, performed in his building.

This permits the manufacturer, on the other hand, in a highly competitive market, to divide the dollars which will be available to him in all phases of producing the function in those areas where he can provide the total function at the least total cost and at the greatest rewards to him through profits.

As a practical matter, this means designing and building into the elevator in the first instance the optimum reliability, the optimum ease of installation and maintenance and the minimum level of maintenance and spare parts expense. The maximum degree of reliability is built into the equipment itself with a corresponding lower degree of maintenance, since field work is always more costly than factory work. But more importantly at all times, the functioning of the equipment to provide safe, reliable vertical transportation is the over-riding requirement on the supplier which in turn insures the basic function of the building.

Compare this with normal defense procurement practices, procedures and policies. The organization procuring the equipment usually buys from one pot and is measured on the extent to which it procures material with the number of dollars available. The organization responsible for maintenance usually buys its spare parts and providing maintenance from another pot. It is not possible at the contracting level to compare the ultimate cost of the two with the ultimate cost of the purchase of the function as a complete package, without regard to which part of the package absorbs how many dollars.

I have oversimplified the situation for the purpose of making a point. There are also many obvious differences between commercial and military production and maintenance. This should not, however, prevent careful analysis to permit the selective application of the functions concept in those areas where it will fit. The function approach has been adopted and is being practiced in some cases. The contractual procedures are available, but the concept needs re-emphasis and extension, particularly in the area, which we are discussing, of electronic and electromechanical systems of great complexity and advanced technology.

Whether or not the practice of actually procuring complete functions is adopted, still the attitude involved, the approach to research, development, production and procurement, is of considerable importance.

Of course, there are major difficulties and road-blocks in the path of achieving the suggested results, which may well dictate higher initial cost but lower cost for the over-all life of the equipment. Some of these are organizational, within the Services. Certainly, the problems presented by General Accounting Office and Congressional review, oriented as they are to low initial price and broad-base competitive bidding, will make the expansion of the function concept difficult and time-consuming. But the advantages to be gained in achieving this, and Mr. Watts who follows me will discuss ways of achieving it, are considerable.

First; the reliability and ease of maintenance and reduced maintenance cost are designed into the equipment in the very first instance as part of the research and development stage.

Second; the total responsibility is placed where it should be placed, on the organization which designed and built the equipment.

Third; this will assure better functioning, which is the sole purpose of the procurement.

Fourth; it will save on manpower in improved efficiency. The manufacturer with the responsibility will have factory-trained personnel intimately familiar with the equipment on hand, as distinct from having the equipment handled, to a large degree, by inadequately trained G.I.'s.

Fifth; it will assure manufacturers approved spare parts in only those quantities required as distinct from the present difficult process of estimating spare parts—frequently in excess of those required—and purchasing them against specs which may bear no basic relationship to systems responsibility and, at least on occasion, are inadequate for the purpose when purchased on competitive bids on a pure price basis.

Sixth; it eliminates the need for detailed primer-type manuals, laboriously created to specifications which are frequently unrealistic and aimed at making a high school graduate the equivalent of a trained electronic service engineer. As we all know, such manuals are costly and, considering the experience of those who frequently have to use them, ineffective.

Seventh; it should substantially reduce requirements for support equipment and personnel.

It has been proved time and again in industry that functional responsibility on the part of the manufacturer of the equipment pays off. Minimum down time of equipment in industry is of basic importance in keeping customers satisfied. Reliability, not just in the equipment but in the complete function is, therefore, of paramount importance to the reputation of the supplier.

Nor need we, I think, be concerned about the justification of such functional procurement from the standpoint of the small business man. No contractor can provide everything that goes into his system or sub-system. The fanning out of contracts, subcontracts and purchase orders through the entire economy is too well known to need emphasis here.

The concept of procurement of functions and functional responsibility placed upon the contractor is fully consistent with the basic concepts of competition upon which our economy and way of life are based and which are written into our procurement statutes and regulations. At no time in history has competition for military orders for basic systems and subsystems been as severe as it is today. Any company whose system or subsystem fails to work suffers in the competitive race, and we all know examples of this. To recapture its position takes years and millions of dollars and sometimes is never done. What company which has full responsibility for the functioning of a basic system or subsystem can afford, if only from the standpoint of its own reputation, to take the risk of not doing its utmost to see that the function is available and operable at all times?

RECOMMENDATIONS FOR IMPROVED PROCUREMENT PRACTICES AS AN AID TO EQUIPMENT RELIABILITY

W. W. WATTS

The previous speakers have reviewed for us current procurement regulations and have indicated that adequate tools exist to assure the end we all seek. Great emphasis has been laid on the necessity for a broader understanding of the vital relationship between initial equipment cost and total useful life cost. They have asked the direct question, "Do current procurement practices actually promote the delivery of unreliable equipment to the government?" These speakers have also stressed the requirement for more emphasis on the functional performance of the equipment as a measure of bid award, with less emphasis on first cost alone. My purpose is to suggest areas where those in charge of procurement policy practices can aid in furthering the reliability objectives of this Symposium.

I believe we can reach our goal with greater effectiveness if we will redirect the emphasis in procurement operations as follows:

a) Place greater weight on the total cost of the equipment, considering its useful life, its ease of operation, its simplicity in introduction to the field from the standpoint of operator training costs, and its contribution to the reduction of maintenance and repair costs. Capt. Malloy has indicated that there is a contracting method which permits this approach. If we are to achieve the utmost in reliability, we must embrace the philosophy I have outlined and use the contracting methods which permit its application.

b) What I have proposed in a) indicates a requirement for a much closer tie-in at the appropriation and budgeting stage between the funds allocated for maintenance and the funds allocated for procurement. An ideal relationship would permit transfer of funds from maintenance to procurement when it can be demonstrated that the total cost of equipment over its useful life will be less by spending more on the initial equipment contract.

c) Means must be found to better analyze the contractor's capability and to give weight to the contractor's demonstrated performance in contributing to the reliability program. Procurement should take into account a contractor's organization structure, test equipment and management policies in this area.

d) Procurement agencies should be given more latitude and authority or exercise a more aggressive censorship under the authority already provided in rejecting procurement requests that fail to adequately recognize reliability requirements which do not provide, in the light of our current knowledge, definitive specifications to insure reliability.

e) While much has been accomplished in providing funds for improved and more reliable components, we still face the incongruous situation where the use of "MIL" parts will not, in too many cases, assure reliability levels we now know are necessary. Too high a proportion of high reliability parts is nonstandard.

f) With the trend toward miniaturization and integrated circuitry, we should pay more attention to the functional specifications, performance and reliability of total circuit segments included in miniaturized or integrated blocks, and less attention to the individual circuit elements included in such assemblies. To put it another way, we should concern ourselves with the input and output characteristics and pay less attention to what goes on in between, provided our reliability objectives are fully met. This is especially important when equipment designs incorporate the throw-away maintenance approach.

g) We must find more effective and faster methods for integrating the lessons of field experience into our design and production practices and work out adequate methods for price redetermination to take care of engineering changes brought on by the introduction of field experience.

h) We must continue our pressure for adequate time in the procurement cycle to provide for prototypes, pilot runs and field tests. We must continue to eliminate telescoping of procurement cycles, which results in these necessary phases running in parallel rather than in sequence.

i) Where GFE is a part of contracting procedures on complex systems, we must provide more accurate information on the reliability specifications of GFE or provide time and money for the prime contractor to evaluate the GFE and work out product modification or improvement as required.

j) We all know that no piece of equipment in a complex system can have reliability greater than that built into the most unreliable component. Let me suggest that a simple key statement be required at the beginning of each proposed equipment specification stating that "the reliability of this equipment is limited by the component described below, which has a reliability index of ________."

k) We should review our evaluation techniques in measuring the performance of Procurement Agencies and Contracting Officers and their aides to the end that "low cost" alone will not be the governing factor in Pay, Promotion and Organi tion Stature.

There is a demonstrated awareness of the n for increased attention to all of the factors that have been discussed by this group. That much progress has been made in this direction is attested by this Seventh National Reliability and Quality Control Symposium. The Department o Defense, the industry and engineering associati and the contractors attending this Symposium a dedicated to improved reliability. Our joint efforts will be more effective if we make it clear those who establish and interpret policy that an enlightened application of these policies can ma a great contribution to reliability.

COMMENTS
MAJ. GEN. W. A. DAVIS

We in the Armed Services welcome constructive criticism from industry, who, while also engaged in the defense effort, can appraise Armed Services procurement policies and actions from somewhat different aspect than we can ourselves outside criticism is often more pointed than self criticism.

The industry comments which we have heard in the main reduce to the following:

a) Contracting Officers do not adequately consider the capabilities of bidders in awarding contracts.
b) Contracting Officers ignore over-all useful life cost in awarding contracts to the lowest bidder.
c) Contracting Officers do not allow enough time for adequate development and evaluation prior to delivery of the equipment.
d) The Armed Services Procurement Regulations compel Contracting Officers to so act.
e) Contracting Officers lack a yardstick for measuring degree of reliability being procured.
f) Two types of contracts used on less than 1 per cent of the procurement dollars could contribute greatly to reliability. These are the performance-incentive-type contract an that particular performance type based on value engineering incentives.
g) MIL Specifications on component parts are inadequate to assure reliability levels necessary for equipments.
h) "Disposal at Failure" maintenance should be emphasized in basic design.
i) Operational maintenance should be largely procured from the equipment manufacturer

as providing better "know-how" than the average G. I.

In this spirit of mutual analysis, I would like to comment on the points raised by industry in this discussion which is on the subject of electronic equipment.

AFR 375-5 directs that a bidder's proposed reliability effort, his past reliability performance and his reliability capability shall be major factors in Source Selection actions. The Aeronautical Systems Center has been applying these criteria for some time, and with surprising results. Proposals on a recent major procurement of Aeronautical Equipment indicated a wide disparity in these reliability areas among major manufacturers bidding on the program. A bar chart was made of the evaluated reliability rankings of the bidders in descending order, and a scaled line drawn on each bar representing the bidder's price. An inverse relationship was apparent; the bidders having the best reliability proposals had the lowest prices, and those having the worst proposals had the highest prices. This does not indicate, of course, that high reliability costs nothing, but it does suggest that manufacturers of the highest reliability competence are by no means the highest cost producers when a firm, measurable, reliability requirement is involved.

The trade-offs between initial cost of equipment including reliability testing and reduction in maintenance cost are subjected, in the Aeronautical Systems Center, to a searching analysis before reliability requirements are specified.

A continuous effort has been underway in the Aeronautical Systems Center to utilize every method open to us to reduce contract administration time on one hand and to start the procurement cycle at the earliest possible point in time on the other. We have great expectations of major improvements in this area; however, it must be recognized that a crucial element of military worth is receipt of reliable equipments in time to meet operational requirements.

The feeling in the Aeronautical Systems Center is in accord with Capt. Malloy's remarks to the effect that a capable contracting officer who is trying to procure reliable equipment will find nothing in the ASPR to prevent him from doing it.

The Aeronautical Systems Center is using, on selected contracts, a very effective yardstick in measuring reliability—the general recommendations of the Advisory Group on Reliability of Electronic Equipment (AGREE), and particularly the realistic tests of AGREE Group 3. We have data which indicates startling savings in maintenance cost of electronic equipment built to meet attainable figures of merit under these tests over equipment built to previous standards.

We have discovered in the analysis of many AGREE test results that on the average, 25 per cent of reliability defects are due to faulty design, 25 per cent to component deficiencies, and 50 per cent due to other conditions within the control of manufacturers' management. Few, if any, were due to state-of-the-art limitations.

The reason more contracts have not been placed containing AGREE Group 3 reliability requirements is the widespread reluctance of industry to accept them, due to fear of the unknown. One of the most gratifying aspects of the present symposium has been the public statements of Mr. Watts and Mr. Hoffman, speaking for major Air Force suppliers, advocating DOD-wide mandatory application of these AGREE requirements, indicating that industry is beginning to appreciate the value of high reliability.

The utilization of special incentive features for reliability in production contracts is, we feel, of doubtful value. Once an equipment is committed to production with a firm, measurable reliability requirement, there is no reliability growth curve. There are production efficiency curves, cost reduction curves, etc., and there can be formal product improvements, but the contractor must meet his reliability and other requirements by design and by management control. Reliability is a measurable parameter like sensitivity, range or power output. As in pregnancy, these are yes or no situations—you have it or you don't.

The report of the Advisory Group on Management of Electronic Parts Specifications (AGMEPS) and present implementing efforts show that the Armed Services are aware of MIL Specification deficiencies and are definitely doing something about it.

The majority of recent development contracts of airborne GFAE contain what we in the Aeronautical Systems Center feel to be the optimum level of design for "disposal at failure" maintenance. The economics of this is a subject of careful analysis on each procurement.

We are well aware of Air Force maintenance problems, but laying aside obvious practical limitations to the use of contractor maintenance, its superiority to G. I. maintenance is by no means unquestionable. One instance is that of an AGREE test being performed on new equipments just off the production line, demonstrating that these equipments had a MTBF of 17 hours. Older equipments of the same type which had been in service for some time with an indeterminate number of line maintenance actions and at least one depot maintenance action having been performed on them were tested under the same conditions as

the new equipments. The resulting MTBF was nearly twice that of the new ones.

COMMENTS
RADM L. D. COATES

Mr. Watts suggested that we might shift funds from operations and maintenance into hardware, with the expectation that an improvement in reliability bought at a higher initial cost would more than pay for itself over the life of the article from a reduced failure rate, lower "down time," reduced spares requirements, and fewer maintenance manhours per operating hour. He also said that reliability or its opposite, unreliability, are built in during design. This of course means during the phase of procurement that is paid for with Research, Development, Test, and Evaluation funds, and while we do have some flexibility in budgeting, his suggestion amounts to bolstering present RDT&E at the expense of future O&M. That we cannot do.

Although this is a conference on reliability, we cannot neglect cost and time. It has been stated and implied throughout this conference that increased reliability costs more in procurement. This is not necessarily true. Reliability generally follows simplicity and tends to be degraded by complexity. Development costs and manufacturing costs also tend to follow simplicity. Reducing the number of parts often improves reliability by eliminating the possibility of failures in rivets, bolts, weldments, and fastenings. So also are handling costs and assembly costs reduced. The use of more reliable bits and pieces may reduce the rejection rate during manufacture, and rejections cost money. I have seen many examples in the Value Engineering Program where a redesign intended only to reduce the cost of manufacture has also plainly improved reliability and maintainability very substantially. I do not at all think we should accept increased cost of procurement as necessary to reliability until we have studied each case on its merits and determined that there is no other way, and that we will get our money's worth. Too often we have bought a reliability program rather than reliability.

I would like to ask Mr. Huggins to be more specific about his recommendations for contractor maintenance of contractors' product. My own experience is mostly in the aircraft field, and although we are used to having contractors' technical representatives with our operating squadrons to advise us on problems with their equipment, I cannot imagine contractors actually taking over the maintenance job aboard an aircraft carrier. A carrier operates airplanes of several different models, each with its own special engine, electronics, instruments, and other components. The number of manufacturers represented in one carrier air group is very large, and I don't think there would be room for them all on the carrier if each manufacturer had a maintenance team aboard. Similar considerations would apply ashore, especially where mobility is a factor, and we would also have the problem of going to war and leaving behind the maintenance teams on which we had come to depend. I'm sure Mr. Huggins did not have this in mind when he made his recommendation, and I would like to ask him just where, and to what class of equipments he would apply contractor maintenance, and what would be its benefits.

COMMENTS
BRIG. GEN. C. S. HAYS

A joint effort by both the military and industry is needed to orient the Congressional viewpoint relative to Department of Defense procurement so that the extremely heavy emphasis Congress is now placing on maximum competition and competitive pricing can be tempered to permit broader consideration of the elements of quality and reliability of equipment.

It is recognized that the Government must seek to clearly define in its procurement data the characteristics of the equipment and the necessary degree of reliability to be achieved. Unfortunately, the ever-growing complexity of electronic equipments and systems makes it increasingly difficult to prepare specifications which are so complete as to assure the extent of reliability and quality desired by the Armed Forces. Further, the dynamic nature of the state of the art often precludes a timely determination as to the reliability which can be achieved where new concepts, principles, and components are involved. Under these circumstances, it becomes extremely important that the contracting officer be afforded the authority and latitude to contract, where appropriate, directly with the firm whose know-how, experience, and technical proficiency indicate that it can attain the most advantageous quality and reliability level.

Admittedly, techniques do, to a degree, exist under applicable procurement law and regulations wherein considerations of quality and increased reliability of equipment can become factors in determining the recipient of the award. However, with the major exception of the Research and Development area, the existing practices, implementations, and interpretations of these

regulations, as a result of Congressional policy, continue to adhere to the concept of awarding contracts to the lowest bidder meeting minimum quality and reliability standards.

Another facet of the problem of improved reliability relates to maintaining equipments in the field. In the event of an emergency situation, the existing difficulties of developing qualified and trained military personnel for purposes of maintenance will be greatly magnified. Although industry can and does assist at the present time by supplying technical representatives, it is not feasible, under emergency conditions, for it to furnish the number of maintenance technicians that would be required in the field, and at the same time to operate its expanded production lines, nor could the military train a large number of skilled repairmen within the time frame permitted. To meet this condition, industry and the military must together exert increased effort to develop, design, and produce equipment of high quality and greater reliability in order that the maintenance aspects can be considerably reduced, or in some instances completely eliminated.

COMMENTS

M. E. JONES

Obviously, we are all in agreement that industry and defense must work closely together in order to provide the most effective weapons at a reasonable cost.

Too frequently, there is a tendency to blame procurement law, regulations and procedures for deficiencies in the quality and reliability of the defense equipment and material we buy. Actually, although our procurement procedures and practices are somewhat cumbersome, the law and regulations are sufficiently flexible to accomplish our needs in an effective manner.

There seems to be general agreement that reliability and quality must be designed and built into the equipment. Practically all of our research and development and much of our prototype production is accomplished under very flexible contracts, i.e., cost-plus-fixed-fee contracts and redeterminable contracts with ceilings which give reasonable protection for risks involved. I believe it is fair to say that most design agents receive the pilot, and in many instances, first production runs of complicated electronics equipment. If quality and reliability have been built, in fact, into the equipment during the research and development, pilot production and production phases, we should certainly be in a position to obtain the necessary technical data and develop a competitive situation among qualified, and I underline qualified, sources at the point of the second production run.

Quality and reliability require ingenuity, money, time and effort but it does not follow necessarily that quality and reliability cannot be achieved at a reasonable price. The Sidewinder program is a glowing instance where the cost was reduced very substantially as the result of competition and, if anything, quality has been improved. For those of you who have not read Mr. Henry Argento's (Philco Corporation) speech concerning Sidewinder before the American Ordnance Association last December, I believe it would be very much worthwhile.

It is not reasonable to expect that there will be less competition in the future. Admittedly, we must exercise greater care in obtaining the necessary technical data to permit competition, and we must award to qualified sources. But assuredly, we must and will obtain competition. It is good for you as well as us. Lack of competition tends to induce complacency and a "Cadillac" philosophy when we are looking for a Ford at a Ford price.

Although price is alluded to as almost the only basis for awarding a contract, this is not so. Research and development contracts are awarded to those most technically qualified. When competition is generated, the concern to which award is made must have experience and ability and must show evidence of good quality control. No one likes to lose a contract, but it is not fair to generalize because of those relatively few instances where a contract is awarded competitively to a company other than the design agent, and the company to whom the award is made has difficulty or fails to perform. Would it not be as reasonable to say the contractor failed because the design agent did not furnish adequate technical data and had not designed quality and reliability into the equipment under contracts which gave him the flexibility to do so?

We must have quality and reliability, but we cannot afford to eliminate competition in the pursuit of these objectives.

Reliability Planning for Space Systems*

NICHOLAS E. GOLOVIN†

My choice of title bears some explanation. The title is a slight variation on that of a series of two articles published recently in one of the missile R&D journals. After reading the first of these papers, my intention was to respond to them before this audience in detail, and in a somewhat critical way. The author's argument, essentially, was that time and money were being wasted in purportedly pseudo-scientific procedures currently employed in reliability analysis and prediction. The title I submitted to the program chairman reflected this intention. After reading the second paper, which had been promised by the author to contain a prescription devised by him for getting better results more cheaply with a simpler and sounder analytical approach, I decided that the author's argument had itself made further response unnecessary. But it was then too late to submit a new title. The result is that my remarks today are only partly appropriate to the announced subject. A more descriptive title might be "Some Technical and Managerial Problems in the Reliability Engineering of Space Systems."

It is perhaps best to begin by indicating how the problems of reliability engineering arise during the course of a development program, and a few of the essential respects in which they differ from some of its other technical problems.

Once a mission concept has been reasonably well defined, its eventual accomplishment is based on the design and construction of a system meeting certain specified quantitative performance requirements for definite, prescribed periods of time. For example, the thrusts of various rocket stages employed must fall within given limits during specified burning time intervals; the guidance and control system must meet definite accuracy and speed of response requirements, within specified tolerance limits, and for certain assigned time intervals; the communications subsystem must have the necessary information handling capacity, and must be operative within certain signal-to-noise-ratio limits for a specified time duration; and so on for other subsystems. The problem of the design engineer, thus, is to develop a detailed plan for the system as a whole which meets all of these performance and operating lifetime requirements, such that when the system is constructed it will have an acceptable likelihood of functioning as designed. This probability of successful functioning could be planned to be either "as high as possible," that is, without any quantitative specification of the value to be attained, or it might be explicitly defined as an over-all, quantitative system goal.

If design engineers are fully responsible for all of the above functions, a question naturally arises as to what a reliability engineer or analyst does, and where he fits into the design and development process. That this question is not wholly trivial is confirmed by the fact that some responsible leaders in both government and industry still argue that there is no essential need for the reliability engineer as such, and certainly none for one who is not under the direct control of the design engineer.

To discuss this question in a useful way, it is necessary to look a little more deeply into the responsibilities of the design engineer and the related skills he must possess. An important fact in this connection, particularly in the case of complex systems, and one which is seldom explicitly realized, is that a system design must fully envision the consequences to over-all system performance of interactions among all of the systems components, over the complete ranges of values likely to be attained by their parameters. These ranges of values are influenced not only by the natural limitations to exact reproducibility of component parameters in the production process, but also by continuous parameter drifts or discrete changes in them occuring as a consequence of uninterrupted operation under the dynamic stress interactions of parts of the system, not only with external environment but also with all other parts of the system itself.

Now the interesting aspect of these complex interaction problems from our point of view is that they are largely stochastic in character and, therefore, are not usually susceptible to valid treatment by the conventional analytical techniques

---

*Address given before the Seminar on "Reliability of Space Vehicles" of the IRE-PGRQC, Los Angeles, Calif., December 5, 1960.

†Rabinow Engineering Co., Inc., Washington, D. C.

available to the design or development engineer. Thus, the problems of assuring adequate manufacturing quality control, those of assuring consistency of component tolerance requirements with successful over-all system performance, and those of specifying both adequate and attainable operating lifetimes for components subjected to loading over extended intervals of time, purely as matters of necessary technical skills, are not included in the training or the experience of the normally equipped engineer or scientist, engaged in system design and development programs. More specifically, the average professional worker in the technologies of interest is accustomed to exact analysis, and has relatively inadequate training in methods of arriving at useful conclusions when only incomplete evidence is available—that is, when the whole spectrum of values under all conditions of interest is not available, and probabilistic models and procedures must necessarily be employed to estimate what the available facts can, at most, logically imply.

It is in these latter situations, in those where guessing and conjecture are inescapable and should therefore be as scientifically well-founded as possible, that the reliability engineer or analyst can make his greatest contribution to a system development program. For those systems where complexity is great, the operating environment poorly defined, and experience data on component behavior meager, even definition of the important developmental problems to be tackled first can hardly be attempted without reliance upon the probabilistic approach. Unfortunately, almost all space systems fall into this category.

Returning now to the question of how functioning of the reliability engineer or analyst and of the design engineer can be correlated, one might hazard the following partial summary and distribution of their principal duties:

Duties Principally of the Design Engineer: 1) define over-all system parameter values consistently with the prescribed goals for the mission, and design the system about a set of selected nominal parameter values for all components of which the system is to be constituted; 2) specify all the operating sequences and operating lifetimes in the system; and 3) modify design and specifications in the light of whatever experience and data are brought to light during development.

Duties Principally of the Design and Reliability Engineers Working Jointly: 1) specify the ranges of parameter values for all parts and components in the system consistent with at least marginal over-all system performance goals under applicable environments; and 2) considering all the variables which must be mutually matched and traded off during system development (cost, time required for development, needed advances in the states of the applicable arts, and so forth), specify an estimate of the probability of mission success which it is reasonable to expect at various stages of the system's progress from first prototype to fully operational status.

Duties Principally of the Reliability Engineer: 1) specify the operating lifetime requirements for all parts, components, and subsystems in the system consistent with all other relevant specifications; 2) develop inspection and testing programs for insuring supplier compliance with the specifications developed; and 3) predict the expected and evaluate the attained reliability of the system and of its major constituents at various stages of the development process, and communicate appropriate advice to the design engineer.

Of course, it could be, and has been, argued that such an explicit approach to reliability is really unnecessary, and that the able and experienced design engineer can arrive at conclusions largely through practiced intuition, and that he can do this more accurately and more quickly when working alone than when assisted by interference from the reliability engineer and his "number's game." Although such an argument might in fact be applicable in certain situations, it is hardly likely to be a reasonable assumption when the systems being dealt with are totally new in concept, in operating environment, in order of complexity, and in needs for prolonged intervals of operation without failure. There are really no "experienced" design engineers having "practiced intuition" for such systems. Obviously, then, some usefulness to insurance of a practical design might ensue from managerial insistence that all design criteria, design decisions and approved specifications likely to affect the probability of a system meeting its over-all performance goals are explicitly defined and defended in quantitative terms. For space systems, where unknowns cover such a broad spectrum, it is then most essential that design engineers and scientists work hand in hand with reliability analysts and engineers in developing the inputs for such definitions and defenses, since these will be, unavoidably, largely probabilistic rather than deterministic in nature.

Now all that has been said so far is applicable to complex systems in general. Since our interests at this Seminar are focused on Space Systems, it is useful in developing our argument to suggest a number of ways in which such systems are unique from a designer's or reliability analyst's point of view.

First, although most space systems are not of substantially greater complexity than many

defensive or offensive weapons systems, the relatively more important systems for future space applications will undoubtedly call for substantially higher levels of reliability than have been generally attained or required in the weapons system field. For example, although a system reliability of 80-85 per cent is fairly respectable from an economic and operational point of view in terrestrial military applications, such a level may well be altogether unacceptable for manned space flight missions. For example, it would probably be generally agreed that an astronaut should be subjected to a much smaller lethal risk in a space mission, than the chance he would take of being shot in a single Russian roulette experiment; but an over-all mission reliability, including pilot safety, of only 85 per cent subjects the pilot to just about the lethal risk of such a Russian roulette experiment. In addition, there is the fact that high terrestrial system reliability is frequently attained through maintenance operations of one sort or another. For space systems, opportunities along these lines are limited and high reliabilities must be attainable on an essentially unattended basis.

Secondly, the environmental conditions for space system operations can be only very crudely reproduced in the laboratory, and flight data in useful amounts and variety will take a long time to be accumulated. This situation further emphasizes that, in the case of complex systems intended for space applications, analytical and simulation techniques based on appropriately developed mathematical models will for a long time play a most critically necessary role. This will be the case also because the usual procedures of testing a long series of prototypes, each incorporating the patch-up benefits of failures uncovered in its predecessors, are just too prohibitively costly for space systems.

These two respects—extraordinarily high reliability requirements and the need for substantial and prolonged reliance on probabilistic models and analytical procedures—are probably the only aspects of space systems development which are significantly special compared to other modern complex systems. The needs for high reliability will, of course, be always with us in this field. The reliance on probabilistic models and analytical procedures can be expected to diminish as operational experience with the space medium and space system hardware is accumulated in sufficient variety and depth.

Aside from these technical aspects of space system uniqueness, it is necessary also to take note of a political factor which may have an important technical implication insofar as Reliability Planning for Space Systems is concerned. This is the matter of USA-USSR competition in space technology.

It is fairly likely that the nature of our political institutions will always tend to keep the fiscal resources allowed for new developments to lag behind those which appear to be competitively required. At least, experience to date suggests that planning at the technical management level should proceed on this, rather than on the contrary assumption. Granted this, a clear implication is that the technical manager must place major emphasis on selection of those of the alternative approaches for attaining space mission goals which offer the earliest prospects of reasonably high probability of success. This sort of approach, involving a trade-off of high performance for earlier attainment of reasonable likelihoods of success in less ambitious missions, may be, operationally speaking, the wisest over-all strategy in our national space program. But any selections for emphasis along these lines must be based on probabilistic studies in adequate depth of various alternative space mission programs. Also, it is fairly obvious that any such approach must involve exhaustive examination of what is currently attainable within the existing states of the art in the relevant technologies, and determination of those lines of further research and development in techniques, componentry and instrumentation most likely to lead to earliest improvements in the states of these arts. Since mission reliability will inevitably be a critical system parameter, particularly in future stages of manned space flight development, such state-of-the-art appraisals must include significant emphasis on estimating what these arts currently offer to increase mission reliability, and what they promise along this line on the basis of future technical development.

Before proceeding to the last phase of this discussion, let us now briefly summarize the argument up to this point. We began by defining the general responsibilities of the design engineer and then explained how the problems of designing complex systems of high reliability placed technical skill requirements on the designer which an engineer of normal training and experience does not possess. Next, we described the skills which the reliability engineer or analyst can supply to amplify the designer's effectiveness and discussed how the functions of the reliability specialist and the design engineer can be usefully correlated. Then we pointed out how the special characteristics of space systems underline the critical need for an explicit reliability engineering approach. Finally, it was noted that this approach was also indicated to be of important value in efforts to

accelerate our relative national rate of progress in space technology.

In view of the apparent cogency of this technical argument, there now arises the obvious question—why is there so much fervent dispute over the usefulness and specific role of the reliability specialist? There is also the next question—what can be done to diminish these controversies or, at least, to ameliorate their undesirable effects?

I am afraid that the only answer to the first question which appears to be consistent with all other related evidence, is failure to recognize that conventional approaches to design and development have become relatively obsolete when applied to complex systems having high-reliability requirements. In those organizations where management is sufficiently alert and determined, these obsolete approaches are currently being patched and bolstered up by what amounts to forced feeding of the design staffs with probabilistic orientations to system analysis, design and evaluation. Since any form of forced feeding, for any reason, is fervently resisted, it is at least partly clear why introduction of reliability specialists into an organization will meet with opposition, particularly from the well-established practitioners of the so-called exact technological sciences. Generally, the more well-established the practitioner, the more fervent and overt the resistance.

Before any comment can be made about the second question, namely, what can be done to help matters, we should first mention some nontechnical, managerial considerations bearing on the general situation—budgets, schedules and objectivity in evaluating or choosing alternative courses of action.

It is quite clear that in a wholly rational and logically managed organization, budgets would be set after technical requirements had been determined, schedules would be established by the only people qualified to set them, namely, the system developers, and questions would never be raised as to the wisdom and objectivity of the Senior Technical Staff in charge of system development! As it turns out, budgets are generally established principally by accountants; schedules are predicated not so much on the hard-earned realities of research results as on what the boss needs to sell the next stage of the program; and obviously, no one is objective except possibly the business management staff, which is the only group in the place not grossly contaminated by knowledge of how the program is really going forward! Moreover, since the Senior Technical Staff is hopelessly dependent on working level design and development engineers, and these characters have no use for reliability specialists whatever, it is quite obvious that we fellows always have an uphill fight on our hands! We can't join the design and development group since we would then lose our objectivity and, anyway, they don't want us; we can't join the Senior Technical Staff because they can't afford a fight with the working level staff; and Top Management won't have us if the Senior Technical Staff snorts too much, and it always seems to! It is thus not too difficult to see that even a sophisticated probabilistic analysis to prove our essentiality for mission success is hardly likely to be helpful except to drive us further to the conclusion that Russian roulette is probably a less risky game for survival than sticking to our jobs!

One might have thought that the right things to have said in the above connections would have been: 1) that budgets should be both ample and flexible to take full and rapid advantage of new knowledge gathered by the research and development program; and 2) that schedules should reflect careful, proved progress in systems development, and that each flight test or other major experiment, would be performed only when quantitative evidence could be provided for an adequate probability of its success, and that the resulting data would advance the over-all development plan. But if I had said anything like this, the accumulating pile of evidence for unpardonable lack of realism among reliability and systems analysts would have been substantially increased, and we, much more than other specialists, must be realistic, you know!

So, as realists, how shall we approach the last question—what can be constructively done to increase the rate of effective interaction between design and development engineers and reliability specialists? The encapsulated, all-around best answer is probably "Subversion through education." Since it is still a pretty good working assumption that, in the long run, "the meek shall inherit the earth," we can ignore those reactionaries who have developed complete faith in their own omniscience, and concentrate our attack on the brighter and more promising deviates in the laboratories, drafting rooms and computing centers. In time, there will develop a growing "Fifth Column" for sharing not just the growing burden of the job but the opposition and criticism as well! To realists, the practical advantages—as well as the poetic justice—of such a course of action should be obvious!

The Space Environment and Its Effects on Materials and Component Parts*

S. N. LEHR†, Senior Member, IRE and V. J. TRONOLONE†

Summary—The best available preliminary information has been gathered on what materials can be used successfully and how these materials react in various space environments. Such information is necessary as a guide to space vehicle design engineers.

In addition to the factors presented here, such items must be considered as: the exact nature of the missile of a space vehicle, the type of orbit, the length of time the vehicle is expected to function, the reliability objective, and similar goals, although regardless of the mission, certain general effects of the space environment present problems which must be met in the design itself. Data have been gathered on these general effects, which include high vacuum, magnetic fields, gravitational fields, micrometeorites, cosmic rays, neutrons, trapped charged particles, and electromagnetic radiation, including ultraviolet light, X rays, and gamma rays. This information is summarized in Table I.

INTRODUCTION

Selection of materials and electronic parts for space applications requires a knowledge of both the known and the calculated or estimated characteristics of space environment. Both types of information are presented in this document, derived from experience and literature surveys.

Since design requirements are based upon specific mission objectives, the capabilities of the launching vehicle, and capabilities of related facilities, information on environment must be considered in the light of its relationship to considerations of the vehicle's size, weight, reliability, performance and mission. For example, space vehicle design is limited by the capabilities of the launching vehicle; therefore the requirements of light weight and minimum size become paramount. Also, allotment of space and weight within the space vehicle is decided on the basis of the relative importance of each piece of equipment in terms of program objectives. At the same time, it is important that reliability objectives receive a priority in equipment design because of the great expenditure of time, effort, and resources involved in any space program. To achieve the lowest possible failure rate and the greatest inherent reliability, materials and electronic parts must be selected with utmost care.

Although data are rapidly accumulating on the nature and effects of space environment, on materials and electronic parts, and on techniques suitable for space equipment design, much remains to be learned. Major work currently in progress will undoubtedly result in the addition of specific information which can be used successfully by the design engineers for future space applications.

THE SPACE ENVIRONMENT

The space environment is defined as the characteristics of space outside the earth's atmosphere, or that region beyond 100 miles above the earth. The environment includes:

1) High vacuum
2) Magnetic fields
3) Gravitational fields
4) Micrometeorites
5) Cosmic rays
6) Electromagnetic radiation
   a) Ultraviolet rays
   b) X rays
   c) Gamma rays
7) Neutrons
8) Charged electron and proton particles.

A literature search indicates that many experimenters have gathered data on this environment for many years. The following summarizes some of these data.

High Vacuum

The pressure at different altitudes is calculated from density measurements, assuming that the perfect gas law holds. Data from rocket

---

*This paper was presented at the Joint Reliability Seminar, Los Angeles Section, IRE, under the sponsorship of the PGRQC, PGCP, AND PGED, Los Angeles, Calif., December 5, 1960.

† Space Technology Labs., Los Angeles, Calif.

TABLE I

Environment	Effects	Design Factors
Temperature	Thermal energy within vehicle produced by solar radiation, earthshine, earth radiation, and internal heating. No convection heating outside earth atmosphere.	Design for temperature control by means of absorptive and reflective surfaced (α/ϵ ratio) with heat control servo circuits. Isolate internal equipment thermally for temperatures between 0° and 60°C depending on requirements. For heat transfer, use radiation and conduction heat sinks. Spin space vehicle to eliminate temperature gradients around surface
Vibration	Unimportant in space (except for launch environment). No acoustic, frictional, or combustion vibration problems except for special applications.	Any vibration, acceleration, or shock levels in space which may occur would be very small compared with those during the boost phase. The equipment must be designed to withstand the levels during boost, and therefore the lower levels encountered in space should pose no problems.
Acceleration	Unimportant in space except for special applications.	
Shock	Unimportant in space except for meteorite and micrometeorite impacts.	
High Vacuum	Sublimation and evaporation of materials occur in high vacuum.	Use materials with low sublimation rates. Allow sufficient thickness for sublimation and evaporation over expected operating life.
	Chemical atmosphere produced by outgassing and sublimation may have corrosive, plating, or chemical effects.	Select material with care to avoid hazardous conditions.
	Electrical arc-over or corona discharge.	Provide adequate insulation material and insulation paths.
Magnetic fields	No effects except for fine instrumentation.	Avoid use of instruments not shielded against variations outside earth's magnetic fields.
Gravitational fields	No effect on materials or parts.	None for materials or parts. For manned vehicles, physiological considerations are involved.
Meteorites and micrometeorites	Collisions with particles of varying sizes occur.	Statistically calculated risk is involved. Use preroughened surfaces or oxide finishes to minimize changes in α/ϵ ratio. Use sufficient outer skin thickness or secondary outer shell to provide protection against small particles.
Ultraviolet light	Increases sublimation rates in high vacuum	Minimize sublimation by selection of materials and by providing sufficient material thickness allowances.
X rays and gamma rays	Ionization of material occurs, possibly causing atomic displacements which produce changes in material characteristics or composition.	Intensity of primary radiation is negligible but shielding with heavy material may be considered for secondary ionizing radiation effects.
Neutrons	Intensity too low to require consideration of atomic displacement effects.	No special precautions necessary because of low intensity.
Trapped electrons	Ionizing radiation occurs primarily in Van Allen belts, possibly causing atomic displacements which produce changes in material characteristics or composition.	Protection required for externally mounted equipment such as solar cells. Space vehicle shell normally provides protection for internal equipment.
Trapped protons	Ionizing radiation occurs primarily in Van Allen belts, possibly causing atomic displacements which produce changes in material characteristics or composition.	For low-energy protons in outer Van Allen belts, protection requirements are similar to those for trapped electrons. For high-energy protons in inner Van Allen belts, there is no known adequate protection.
Biological organisms	Contamination of space environment.	Sterilization of vehicle and contents now required by international agreement to prevent possible biological contamination of lunar or planetary environment.

flights up to 700 km (425 miles) have been reduced and several models have been assumed from the average molecular weight of the atmosphere. Because of the inability to measure pressures in the range of interest, direct measurements are not possible.

There have been a number of calculations of the ambient pressures at various altitudes (Fig. 1).

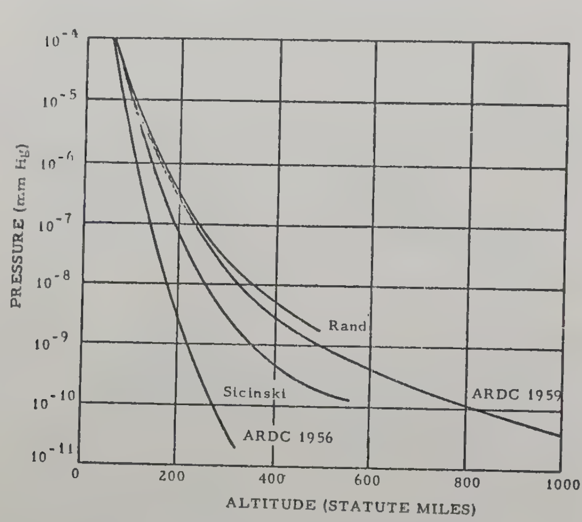


Fig. 1. Pressure vs altitude (for several atmospheric models).

The ARDC 1956 model atmosphere estimates data up to 300 miles[1]. Sicinski and his associates have made further calculations[2]. Two possible models of the upper atmosphere have resulted from studies published by the RAND Corporation in 1958[3].

The latest and probably the most authoritative model of the atmosphere is the result of ARDC 1959 studies[4]. This latest model gives densities 20 times higher than the 1956 model at 600 km and only half that of the 1956 model at 120 km. The data are extrapolated beyond 700 km (425 miles). In free space, remote from the solar system, the pressure may be as low as 10^{-16} mm of mercury, which corresponds to one hydrogen atom/cm^3 of space.

Magnetic Fields

The maximum horizontal component of the earth's magnetic field is 0.3 gauss at the magnetic equator[5],[6]. Theoretically, this field varies inversely as the cube of the distance from the center of the earth. This is true up to an altitude of about 300,000 feet (60 miles). Above 300,000 feet a sharp decrease is noted[6],[7] in the measured field intensity, which is associated with the presence of ionized particles.

Results of Explorer VI and Pioneer V experiments verify that a region of ionized particles exists at an altitude of 5 to 7 earth radii and that another disturbed region of the magnetic field exists at 10 to 14 earth radii.

Readings in the 5 to 7 earth radii area varied from 150 to 10 microgauss. In the 10 to 14 earth radii area, the magnetic field is irregular due to reactions between the earth's magnetic field and the solar winds. Beyond this distance, there is evidence of a magnetic field greater than 10 microgauss[8].

Gravitational Field

The acceleration of gravity due to the earth's gravitational field is given by

$$g = g_o \left(\frac{r_o}{r_o + Z} \right)^2$$

where g_o is the acceleration of gravity at a distance r_o from the center of the earth, and Z is the altitude above r_o. At the surface of the earth r_o = 6,357,000 meters (3951 miles), and g_o = 9.807 meters/sec^2 (32.17 ft/sec^2) at 45°N latitude[1].

Micrometeorites

Clouds of particles or micrometeorites appreciably larger than molecular size exist in the outer space. They are presumably the debris from other bodies in the solar system and for the most part are very small. These particles are observed by reflected light in the outer solar corona and from zodiacal light in the region of the earth, and the observations indicate that they are generally larger than one micron and in the region of the earth's orbit may be larger than 10μ.

The velocity of these particles relative to the earth varies from 11 to 73 km/sec and the average density is approximately 3.4 g/cm^3[9], although several experimenters believe that "dust balls" may have densities as low as 0.05 g/cm^3[9]-[12].

The best fit to the data obtained indicates the following particle flux, which is plotted on Fig. 2.

N = number of particles larger than R/cm^2sec

$$= \text{exponent} \left[-100 \left(\frac{4 + \log R}{9.4 + \log R} \right) \right]$$

where R = particle radius in centimeters.

Mayo[13] calculated the hours between hits on a 3-m-diameter vehicle vs meteorite diameter.

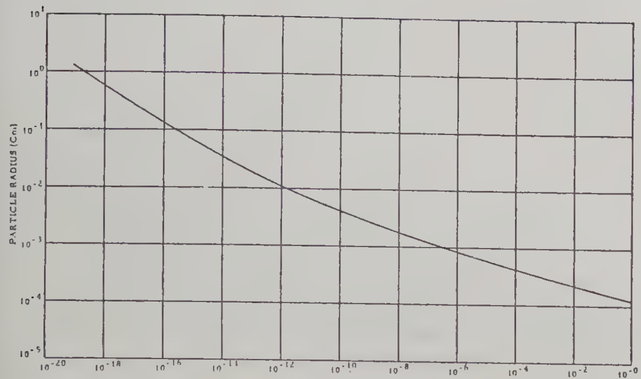


Fig. 2. Integrated flux density (number of particles larger than indicated size/cm^2/sec.

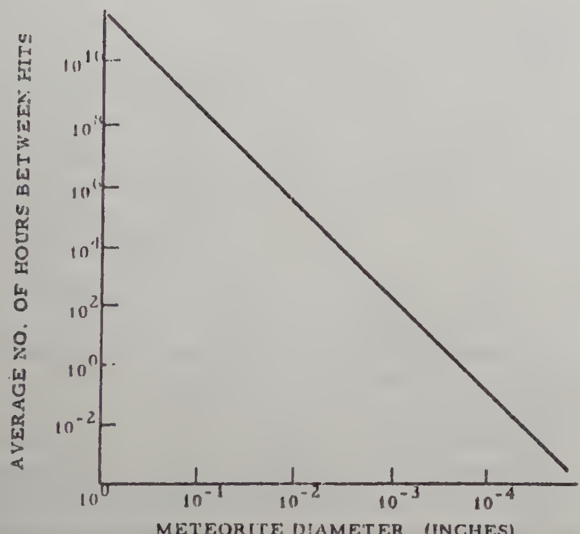


Fig. 3. Frequency of hits by meteorites of various diameters on a 3-m-diameter vehicle.

These data are presented in Fig. 3.

Cosmic Rays

The primary cosmic flux consists of particles whose energy ranges from a few Mev upwards of 10^9 Bev. Excluded from this category are thermal, X-ray, and optical radiations. The relative percentage of cosmic flux constituents is given in Table II[14]-[17].

The maximum particle intensity is about two particles/cm^{2}sec, and is a function of the geomagnetic latitude[14].

The maximum ionization in any material due to cosmic rays is one milliroentgen per hour. Fig. 4 plots the maximum ionization in 24 hours as a function of altitude and geomagnetic latitude[14].

TABLE II
RELATIVE PERCENTAGE OF COSMIC FLUX CONSTITUENTS

Particle	Percentage	Relative Number of Nucleons
Protons	80	0.4650
Alpha	19	0.4419
Li, Be, B	Negligible	Negligible
C, N, O	0.66	0.0535
Na, Mg, Al, Si	0.12	0.0186
S, A, Ca	0.04	0.0081
Fe	0.02	0.0063

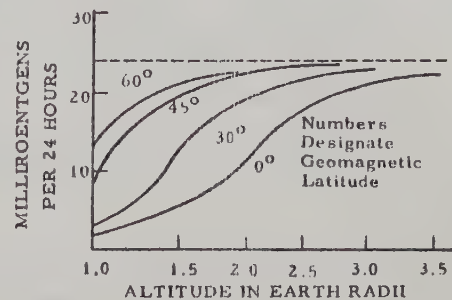


Fig. 4. Maximum ionization in 24 hours at several geomagnetic latitudes.

Data on extensive experiments covering the performance of complex electronic equipment at high altitudes are already available[14],[16]-[18]. In no case has equipment failure been competently attributed to effects of cosmic radiation.

Electromagnetic Radiations

Ultraviolet Light and X Rays: The total radiation from the sun in the several-thousand-mile range above the earth is 7.38 Btu/ft^2-min[1],[19]. This energy could be divided into four ranges of radiation, each with the following percentage of the total energy:

Infrared	7000 Å and up	51.0 per cent
Visible	3800 Å to 7000 Å	41.0 per cent
Near ultraviolet	2000 Å to 3800 Å	7.5 per cent
Far ultraviolet	1 Å to 2000 Å	0.2 per cent

(Å = angstrom units = 10^{-8} cm).

The total energy in the ultraviolet region is about 0.5 Btu/ft^2-min. The energy in the X-ray region (1 Å to 100 Å) is negligible.

Gamma Rays: Observations of cosmic ray fluctuations associated with solar flares accompanied by intense geomagnetic storms indicate that intense pulses of gamma rays are injected

into space[20]. These pulses are difficult to detect due to the shielding effects of the atmosphere.

There is no evidence that these events occur often enough to be significant, and it could be assumed that the gamma-ray contribution to radiation intensity is negligible. They would be significant in communication, however, because of the bursts of radio noise.

Neutrons

Apparently there are no neutrons in the primary cosmic flux[17]. This is consistent with the 12-minute half-life of the neutron. Any neutrons emitted by a source would have adequate time to decay to a proton and electron before reaching the earth's field. The neutrons present in the vicinity under consideration are due to the upward moving (albedo) components of the neutrons formed by reactions of primary cosmic radiation with the upper atmosphere.

The cosmic radiation intensity is roughly two particles/cm^2 sec. The intensity of albedo neutrons probably does not exceed this quantity because the cross section of the cosmic particle-neutron reaction is not high[21]. The albedo neutron flux will decrease inversely as the square of the distance above the atmosphere. It is safe to assume that the neutron flux above the atmosphere would not exceed one neutron/cm^2 sec. Since the threshold of neutron damage to any material or component is at least 10^{11} NVT (total integrated neutron flux), even after years of exposure to this level (3.5×10^7 NVT each year), the total integrated flux due to the albedo neutron in any equipment should be insignificant.

Charged Particles—Electrons and Protons

The first experimental evidence of trapped radiation around the earth resulted from the experiment of Van Allen and his associates on Explorer I. Additional data were received from Explorers III, IV, and VI and Pioneers I, II, III, and IV[22]-[28]. Pioneer I traversed the radiation zone radially, and the ionization radiation measured as a function of distance above the surface of the earth is plotted in Fig. 5. This curve indicates that the level exceeds two roentgens per hour between 4000 and 24,000 km altitude and between 30°N latitude and 10°N latitude. It peaks at about 10 roentgens/hr at 10,000 km and 20°N latitude.

Pioneer II indicated the variation of the field with latitude at an altitude of 1525 km. This is shown in Fig. 6.

Although at higher altitudes this curve would not be exact, the general tendency of decrease in ionization with increasing latitude is still expected.

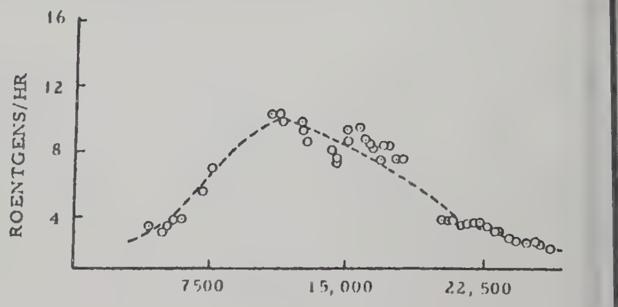


Fig. 5. Ionization radiation measurement of the radiation zone.

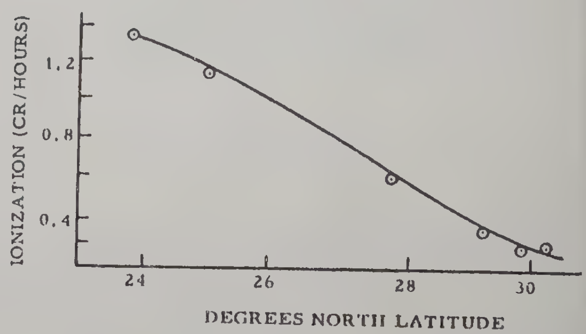


Fig. 6. Variation of radiation with latitude.

Pioneers III and IV gave the first indication that two or more ionized regions exist. Pioneer IV showed a large increase in radiation in the outer zone over the values measured by Pioneer III without a corresponding increase in the inner zone[28],[29]. This suggested the possibility of a different origin of the particles in the two zones.

The orbit of Explorer VI provided excellent opportunity for observing the changes in the two regions over a period of time. The data confirmed the relative stability of the inner zone and the large time variation of the outer zone[28]. Fig. 7 plots Explorer VI isointensity contours.

From these data, it is reasonable to deduce that there are two sources for the trapped particles[30],[31]. The inner belt, containing largely high-energy protons, probably results from the decay of the albedo neutrons, while the outer belt, containing largely low-energy electrons, is probably of solar origin. This would explain the time variance of the outer zone as a function of solar storms.

Summarizing the data reported by Van Allen, Rosen, and others, an approximate plot of electron intensity above 20 Kev can be deduced for an

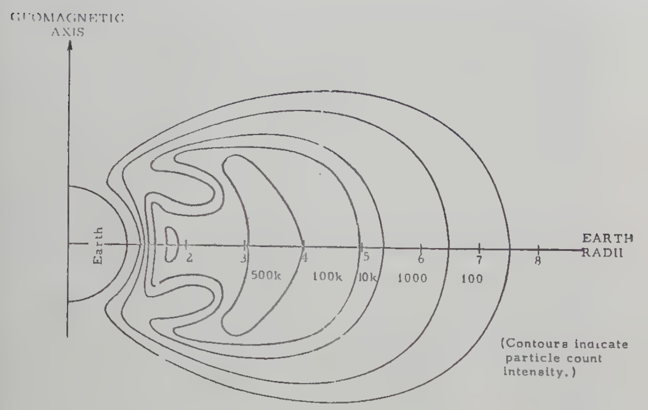


Fig. 7. Explorer VI isointensity contours.

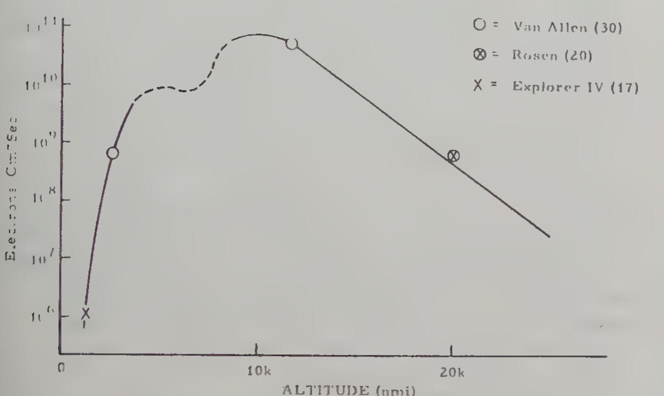


Fig. 8. Electron intensity above 20 Kev (equatorial orbit).

equatorial orbit (Fig. 8).

An approximate plot of the proton intensity for several threshold energies is presented in Fig. 9. The intensity at the 20-mev threshold is estimated from the best available data[17],[20],[30],[31].

EFFECTS OF THE SPACE ENVIRONMENT ON MATERIALS AND COMPONENT PARTS

Effects Other than Radiation

Besides radiation, such factors as temperature, high vacuum, micrometeorites, and gravitational and magnetic fields affect missile and space vehicle design.

Temperature Effects and Control: Temperature effects in space environment are the result of thermal radiation from direct sunlight, from sunlight reflected from the earth, and from direct earth radiation, as well as from heat generated internally within the space vehicle[32],[33].

The relative contributions of the three thermal

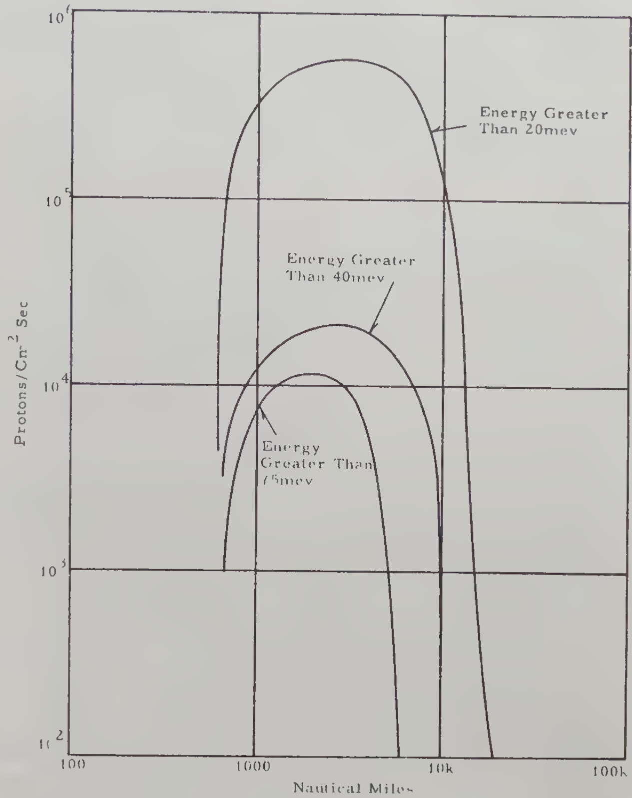


Fig. 9. Proton intensity at the geomagnetic equator.

radiation sources change with distance from the earth. For example, a few hundred miles above the earth the instantaneous power incident on a 20-inch spherical satellite is approximately 67 cal/sec from direct sunlight, from 0 to 25 cal/sec from earthshine, and of the order of 12 cal/sec from direct earth radiation. Contributions from earthshine and from direct earth radiation fall off with altitude above the earth. For instance, the contribution at 4000 miles is only 20 per cent of that at 200 miles. The contribution from direct solar radiation does not change significantly for any earth satellite except for periods of eclipse by the earth, but may change drastically for space probes whose distance from the sun may differ appreciably from that of the earth.

Two techniques for thermal control of electronic packages in space vehicles are used, passive temperature control and active temperature control.

Passive temperature control relies on selection of a package surface material with the proper ratio of solar heat absorptivity to infrared emissivity (a/e) to control the thermal radiation balance of the package for the desired internal temperature. Principal factors affecting this balance include solar energy, exchange of radiant energy

with the space vehicle skin, and heat transfer from electronic equipment. Over a period of time, the space vehicle surface will be sufficiently changed by the effects of micrometeorite sputtering, ultraviolet radiation, and particle radiation so that the absorptivity-to-emissivity ratio will be altered significantly, and must be compensated for in equipment design.

The second technique, active temperature control, relies on controlled heaters or thermoelectric coolers to maintain the desired temperatures. Heat is transferred from electronic components to radiating surfaces through preselected conduction paths. Heat gains or losses from other equipment surfaces not selected as radiators are virtually eliminated by use of a multilayer aluminum foil thermal radiation shield with an effective thermal conductivity in vacuum of 2.5×10^{-5} Btu/hr-ft^2-°F. An alternative type of active temperature control uses mechanically operated temperature-sensor-controlled radiation louvers which balance the absorptivity-to-emissivity ratio.

High-Vacuum Effects: Two important effects on solid materials result from high vacuum. First, sublimation and evaporation are enhanced by the absence of an atmosphere because molecules leaving the surface of a material do not make collisions that return them to the surface. Therefore, if a space vehicle is high enough so that the mean free path of the molecules is long compared to the size of the craft, any molecule that leaves the surface can be assumed not to return. Second, a partial or complete removal of the surface film of gas which covers all material in the sea level atmosphere is affected. This depletion of surface gas layers has an effect on the properties of materials[37].

Plastics: The effects of high vacuum on plastic materials are varied. In general, it can be said that the basic polymer of the plastic is not likely to have a high enough vapor pressure to cause a significant loss of material. However, plasticizers used in many plastics have relatively high vapor pressures and therefore may cause the loss of large amounts of material. As can be expected, the rate of diffusion of the plasticizer within the plastic plays an important part in the over-all loss.

Tests conducted on several samples indicate that exposure does not have significant effect on the weight loss and flexural strength for periods up to 500 hours, to ultraviolet in the range of 2000 to 6000 Å, and pressures in the 10^{-6} mm Hg range.

Metals: The effects of high vacuum on metals can be calculated from kinetic theory

$$G = \frac{PM}{\sqrt{2_{\pi} MRT}}$$

where G is the rate of loss per unit area of ex- posed surface, M is the molecular weight of the material, T is its absolute temperature, P is it vapor pressure at temperature T, and R is the universal gas constant[35].

By applying this formula to elemental metals it will be seen that in no case is the loss of stru tural significance except at highly elevated tem- peratures (which are not likely to be encounter by spacecraft). However, some metals (e.g., cadmium, zinc, and magnesium) sublime enough at relatively low temperature to warrant attenti when used for nonstructural applications such a platings or optical films.

The high-temperature, creep-rupture, and fatigue properties of metals are appreciably af- fected under vacuum tests[36]. At high tempera tures and low stresses, creep-rupture specimen are stronger in air than in vacuum, but at low temperatures and high stresses there is a rever sal and they are stronger in vacuum. Although limited fatigue data show a similar behavior, tests are not sufficiently complete to be conclusive. A mechanism to explain this reversal involves two competing processes: 1) strengtheni by oxidation, and 2) reduction in strength by low- ering of surface energy. By definition, surface energy is the work required to produce a unit area-of-fracture surface in a brittle material with no plastic deformation.

The higher the vapor pressures of a material, the more rapidly it sublimes[37]. A plot of vapo pressure against temperature (Fig. 10) indicates the severity of the problem for a number of materials. The metals on the right portion of the figure, including the lightweight structural metal titanium, beryllium, aluminum, and gold, would not sublime at significant rates at their expected

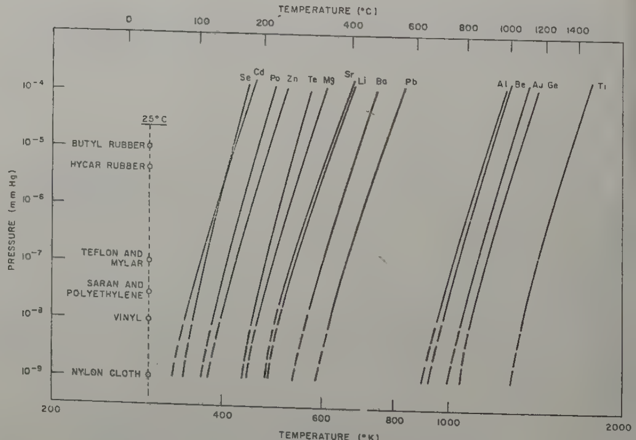


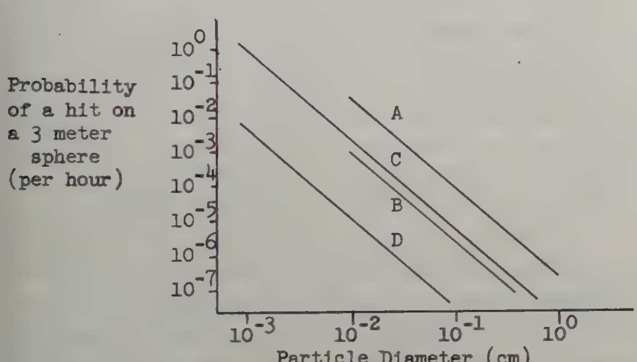
Fig. 10. Sublimation of metals in space (F. J. Clauss).

use temperatures. These materials should not present a problem in high vacuum due to their lower vapor pressures. Metals which have higher vapor pressures would be a potential source of trouble. For example, magnesium and also lithium, with which magnesium is sometimes alloyed, could lose appreciable amounts. Zinc and cadmium, both often used for electroplating parts, have higher vapor pressures than magnesium. Their use within satellites could cause short-circuiting problems, due to evaporation and then plating out on exposed electrical surfaces. A space vehicle thus can actually be thought of as a vacuum plating chamber, since any volatile material would leave the warm surfaces and plate out on the cooler surfaces.

The phenomenon of sublimation from metals can be retarded by inorganic surface coatings, such as oxides, which often have lower vapor pressures than the metals from which they are formed.

Vapor pressures for plastic and elastomer materials at room temperature (the left portion of Fig. 10) are quite high in comparison to the metals.

Micrometeorite Effects: Micrometeorite particle damage to a spherical space vehicle with a diameter of 3 m near the earth can be estimated from the following curve.



Curves A and C represent the upper and lower bounds of the estimates from [39]; curves C and D the upper and lower bounds from [38]. Curve B is probably the best estimate to date and summarizes the latest available Whipple data. Using this curve, the best estimate of particle damage to a 3-m sphere is shown below.

Penetration of Aluminum	Frequency of Penetration
0.1 cm	Once in 50 days
0.32 cm (1/8 in)	Once in 2000 days
1.0 cm	Once in 100 years

Vehicle puncture is, therefore, a statistical probability and the outer shell thicknesses or the possibility of using a secondary outer shell should be a function of this probability.

Erosion and general roughening of the outer shell will effect the thermal considerations, and these effects should be taken into account in the thermal design.

Other Environmental Factors: Several factors in the space environment require consideration for special applications but do not generally affect the design of equipment.

Vibration, acceleration, and shock levels encountered by an orbiting space vehicle or a space probe are very small in comparison with those experienced during launching or boost phases. Since the equipment must be designed to withstand the levels during launching and boost, the lower levels encountered in space should pose no problems. For other space vehicle applications involving re-entry, recovery, landings, or other related missions, the effects of vibration, acceleration, and shock may become major considerations in equipment design.

Gravitational fields and magnetic fields to date have required little consideration in the selection of parts or materials for space vehicles. The decreased gravitational fields encountered with the increase in distance from the earth, however, do have effects which would require consideration in the case of manned space vehicles.

Magnetic effects, which are unimportant for the design of space equipment at present, might become important in space vehicles designed for advanced applications. At present, the only serious consideration of magnetic effects is for fine instrumentation which may need shielding to prevent excessive variations outside the earth's magnetic fields.

Effects of Radiation Environment in Space

Background and Definitions: Both electromagnetic (zero rest mass) and particulate (finite rest mass) radiation will be considered. Electromagnetic radiation includes ultraviolet light, X rays, and gamma rays (photons). Particulate radiation consists of electrons, protons, neutrons, alpha particles, and a small amount of higher atomic number particles [40], [41]-[43].

Radiation may also be classified as ionizing or nonionizing. Ionizing radiation is capable of producing ions in the material through which it passes. Of the types of radiation in which we are interested, only neutrons are nonionizing in their primary effect.

In addition to ionization, which is the loss of an

electron by an atom or molecule when ionizing radiation passes through material, excitation also results. Excitation is the process in which an atom or molecule gains energy without being ejected, and in many cases, is as important in producing secondary radiation. There is also the effect in which a particle radiates part of its energy in the form of electromagnetic waves when it interacts with matter. This process is known as bremstrahlung and is usually not an important radiation source for material damage. These processes always occur simultaneously when ionization radiation interacts with matter.

The basic assumption in radiation effects studies is that changes to a material under irradiation result only from the transfer of energy to the material. Radiation which passes through a material without transferring any energy has no effect on the material. Total radiation affecting a material is described by the energy flux, number flux, or exposed dose. Energy absorbed is described by the absorbed dose.

The absorbed dose is useful in estimating radiation tolerance, without regard to the kind of radiation, for materials such as organic compounds (plastics, elastomers, oils, greases) and many inorganic compounds.

For other materials (metals, ceramics, or semiconductors, for example), the radiation effects are proportional to the exposure dose rather than absorbed dose. For a metal in a reactor, the most damaging component of the radiation field is the fast neutron; the effect is proportional to the time-integrated fast neutron flux (neutrons/cm^2). Different units are therefore used for different materials.

Penetration of Radiation in Material: An important effect of radiation on material involves range or penetrating power. Since an alpha particle is relatively massive and highly charged, it interacts strongly and penetrates only a small distance before stopping completely. In this distance it gives up a large amount of energy, predominantly by interacting with and scattering electrons, resulting in a very high density of ionization. Similar considerations hold true for protons. Electrons, although charged, are less massive and penetrate further.

Electromagnetic radiation, on the other hand, is highly penetrating. Similarly, a neutron, being electrically neutral, can travel relatively far before slowing down. Neutrons, X rays, and gamma radiation are attenuated exponentially in passing through matter, and it is impossible to fix a definite distance of penetration, as is possible for the charged particles.

Since neutrons are attenuated by collisions with atomic nuclei, rather than by electron interactic as is the case with gamma radiation, a heavy ma terial such as lead does not very effectively shield against fast neutrons. Very little energy loss occurs in collisions of neutrons with lead atoms. Hydrogenous materials such as water or plastics are most effective in shielding against fast neutrons, since hydrogen nuclei and neutrons have the same mass.

For charged particles, the penetration range listed in Table III is the thickness required to reduce the intensity essentially to zero. For gamma rays and neutrons, the thickness is that required to reduce the intensity to half the incident value.

TABLE III

COMPARATIVE PENETRATING POWER OF TYPES OF RADIATION

Radiation Particles	Energy (mev)	Penetrating Range (inches)	
		Water	Aluminum
Alpha	1	0.002	0.001
	10	0.01	0.004
	100	0.4	0.14
Proton	1	0.001	0.0004
	10	0.04	0.014
	100	2.3	0.74
	300	24.0	7.9
Electrons	1	0.14	0.055
	3	0.58	0.21
Gamma Ray	1	4.5*	1.7*
	5	9.1*	3.7*
Neutrons	2	3.0*	3.5*

*Thickness necessary to reduce the intensity by 0.5.

Radiation Damage Mechanisms: Changes in properties of materials resulting from high-energy radiation may be interpreted in terms of several types of defects produced in the material by the radiation. These defects are: vacancies, interstitial atoms, impurity atoms, replacement collisions, thermal and displacement spikes, and ionization effects.

Effects on Metals: When a metal is exposed to ionizing radiation, the energy absorbed in ionization and excitation appears as heat and results in temperature rise in the metal.

When the radiation causes atomic displacements, vacancies created in the lattice structure are more serious. Secondary collisions may produce as many as 1000 displaced atoms per incident particle with 2 Mev neutrons[41].

Radiation can cause: 1) stabilization of phases in a temperature region which lies outside the

normal stability region of the particular phase, 2) formation of metastable phase in supersaturated alloys, 3) formation of Frenkel defects (vacancy and interstitial) which influence diffusion-controlled phenomena, 4) thermal spikes, and 5) transmutations[45].

The following general summations of expected radiation effects, although not a complete quantitative evaluation for all metals and metal systems, summarize many of the effects of radiation on metals.

Gamma or X-ray radiation has primarily an ionizing effect which does not change the metal properties. High-energy secondary radiation (electrons), however, may have additional effects. Electrons (or beta particles) do not have sufficient mass to cause any appreciable effects, since the energy rarely exceeds 1 Mev. Fast neutrons appear to have the greatest effects on the physical and mechanical properties of structural metals. High-energy protons and the heavier charged particles are both similar in effects with damage mechanisms mainly in the form of atomic displacements. In addition, protons may come to rest as interstitial hydrogen which may effect metal properties.

Neutron effects on various metals have been studied at integrated fluxes between 10^{15} and 10^{22} fast NVT, primarily at temperatures between 30 and 400°C. Properties of metals can be further changed either by increasing the neutron dose or by decreasing the irradiation temperature. Similarities between cold work and radiation damage have been noted. In general, the properties of metals such as thermal conductivity, electrical resistivity, and density, do not appear to undergo any appreciable changes upon irradiation, even with fast neutrons. However, those properties of metals which are structure-sensitive (yield strength, hardness, ductility, etc.) usually experience a considerable change upon prolonged exposure to fast neutrons.

Effects on Inorganic Materials: Inorganic materials include bond types ranging from purely ionic through ionic-covalent (ceramics, glasses, mica) to pure covalent (silicon, germanium, carbon).

From an atomic point of view, a typical example of a purely ionic compound (a salt such as sodium chloride) consists of a fixed network of positively and negatively charged ions held together by strong electrostatic forces. Fast neutrons produce atomic displacements by collisions with the lattice ions, resulting in the interstitial-vacancy type of radiation damage. Also, electrons ejected during ionization processes may become trapped interstitially, resulting in "coloration centers"[41],[46].

Typical of the ionic-covalent bond are ceramics such as beryllium oxide and aluminum oxide, glasses such as the silicates and borates, and certain minerals such as mica. The principal damage mechanism occurs by atom displacement, with changes in density, thermal conductivity, and electrical conductivity resulting from the increased lattice disorder.

Typical inorganic materials which are essentially covalent in structure are the elements carbon, silicon, and germanium, and compounds such as silicon carbide, indium antimonide, and zinc oxide. Both the electrical and thermal conductivity of graphite decrease upon irradiation.

Silicon and germanium, along with compounds like indium antimonide, are well-known semiconductors. Irradiation with gamma rays results in appreciable leakage currents; this effect quickly disappears upon removal from the radiation field. Permanent effects, however, are produced through the process of atom displacement.

Effects on Organic Materials: Organic materials are susceptible to damage from all types of nuclear radiation.

Radiation damage in organic materials results from the formation of foreign compounds. As nuclear particles traverse a material, energy is transferred to the electrons and nuclei of individual atoms in quantities sufficient to break the bonds or linkages which bind the atoms into molecular groups. After passage of the radiation particle, fragments of the disrupted molecules react chemically to form new compounds. Concentration of these impurity compounds increases with increasing radiation and results in correspondingly greater changes in physical and mechanical properties.

Elastomers as a class of materials are among those most susceptible to radiation damage. Energy absorbed by elastomers from ionizing radiations disrupts the bonds between the atoms and destroys the balance between the inherent freedom of motion of the chain-like molecule and the degree of cross-linking or chemical bonding between the individual chains. As a result, hardness and tensile strength are increased and compressibility and elongation are decreased.

Most elastomeric materials are not satisfactory for use beyond a gamma dosage of 10^8 ergs gm^{-1} (based upon carbon) and a neutron flux of 10^{15} neutrons cm^{-2} sec^{-1}. Natural rubber is the most radiation-resistant of the elastomers. Styrene-butadiene rubber is the most resistant of the synthetic elastomers. Silicones and fluorine-based polymers are below average in radiation resistance.

Plastic materials likewise are susceptible to

damage by all types of radiation because of the ease with which molecular structure can be reoriented. Since plastics are also polymers, the reorientation consists of the formation of new bonds between chains, the breaking of chains, the evolution of gases, the reaction with the environment, such as the absorption of oxygen, all resulting in changes in physical and mechanical properties.

Among the plastics, materials such as mineral-filled polyester, mineral-filled phenolics, polyethylene, polyethylene teraphthalate (Mylar), polystyrene, polyvinyl chloride, and polyvinyl formal will perform satisfactorily to 10^9 ergs gm^{-1} gamma flux (based upon carbon) and 10^{18} neutrons cm^{-2} sec^{-1}. Some unfilled polyesters are below average in radiation resistance and are unsatisfactory for most radiation applications.

Phenomena of interest in many organic polymers are cross-linking and scission. Cross-linking is the formation of bonds across polymer chains due to displacements of hydrogen or other atoms outside the carbon chain. Scission is the breaking of a carbon chain. A material which cross-links strongly will increase in strength with radiation up to a certain point. One which scissions strongly will decrease in strength with radiation.

Various organic insulating materials are listed below in decreasing order of effective lifetimes under radiation[43],[47].

1) Polyethylene
2) Silicone Rubber
3) Mylar
4) Polystyrene
5) Polyester
6) Epoxies
7) Nylon
8) Polypropylene
9) Neoprene
10) Butyl Rubber
11) Vinylidene Chlorides
12) Kel-F
13) Teflon.

Polyethylene, which cross-links strongly, is the best and Teflon, which scissions strongly, the poorest.

Effects on Electronic Parts: Electronic parts reflect radiation effects on the material used in their construction. In addition, other effects are a function of the electronic circuitry. In general, digital is more affected by transients than analog circuitry, while the latter has a lower total dose tolerance.

Transient effects usually result from ionizing radiation and are a function of the dose rate. The conductivity of several insulations as a function of

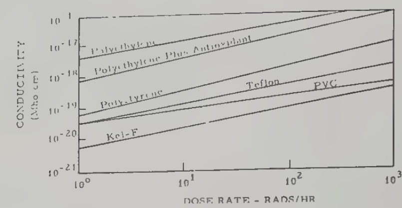


Fig. 11. Conductivity of insulations as function of dose rates.

dose rate is shown in Fig. 11. Obviously, higher dose rates increase the leakage of the materials[48],[49].

Primary atomic displacements as well as displacements due to secondary radiation usually result in permanent damage.

Electronic parts which contain organic materials are damaged by radiation proportional to the exposure dose. For cables and wire leads, connectors, and transformers, which use organic insulating materials, the threshold of damage to insulation is much lower than any effect on the metal.

Most electronic parts are damaged by radiation proportional to exposure dose, which is a function of the incident radiation. The thresholds of damage for the most commonly-used components under fast neutron and gamma radiation are listed in Table IV[50],[51].

TABLE IV
RADIATION DAMAGE THRESHOLDS FOR ELECTRONIC PARTS

Electronic Part Types	Fast Neutrons (NVT)	Gamma (Roentgens)
Resistors	10^{18}	10^9
Capacitors	10^{15} to 10^{18}	10^6 to 10^9
Transformers	10^{18}	10^9
Vacuum Tube	5×10^{15} to 10^{18}	10^6 to 10^9
Rectifiers (thin base Si)	1.5 to 10^{15}	10^6
Computer Diodes (Si, Ge)	10^{13}	10^4
Transistors (Si)	10^{10} to 10^{12}	10^3
Transistors (Ge)	10^{11} to 10^{14}	10^4
Dry Cells	10^{15}	5×10^{16}
Lead-Lead Oxide Battery	10^{15}*	3×10^6*
Alnico V Magnets	10^{17}*	7×10^8*

*No significant damage.

The variation in small-signal B (current gain) for several transistor types has been measured. One of these, type T1075, showed no variation in gain for exposure to 10^{14} NVT. The curve

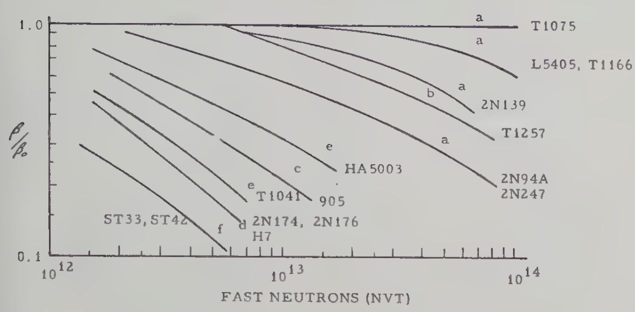


Fig. 12. Neutron radiation effects on current gain of several selected transistors. (a) HF germanium p-n-p. (b) HF silicon p-n-p. (c) HF silicon n-p-n. (d) Power germanium p-n-p. (e) General-purpose germanium p-n-p. (f) Switching silicon n-p-n.

(Fig. 12) indicates clearly that germanium transistors are more radiation resistant than silicon and that HF narrow-base devices are better under radiation than LF thick-base devices[52].

Little information is available on the effects of protons on these electronic parts. Bombarding bulk germanium and silicon with deuterons has resulted in large changes in resistivity and in the case of germanium, a change from n- to p-type [50],[51]. Empirical calculations have been made[53] on the number of displacements/cm^3 per incident proton with energies below and above 100 Mev. Lark-Horovitz[40] believes that the threshold energy for displacement in silicon and germanium is 30 ev, resulting in approximately 1000 displacements/cm^3 per incident proton.

Semiconductor devices are sensitive to radiation and cannot practically be protected against the high-energy particles in the Van Allen belt. Expected life in this area may be only a few months. The choice of semiconductor devices and circuitry necessarily must be a compromise. For maximum reliability, silicon semiconductors should be used, especially where temperatures may be higher than normal. In terms of radiation tolerance, germanium semiconductors may have as much as one hundred times the anticipated life of silicon devices. Tests in nuclear reactors show that semiconductors with smaller base widths are inherently better under radiation. For power rectifiers, the lifetime in a reactor has been found to be a function of base width, with an increase of 80 times for a decrease in base width from 4.5 to 0.8 mm. HF transistors, which must have thin bases, are inherently more radiation tolerant[54]. The use of high-gain amplifiers with large amounts of feedback will also increase the radiation lifetime of a semiconductor.

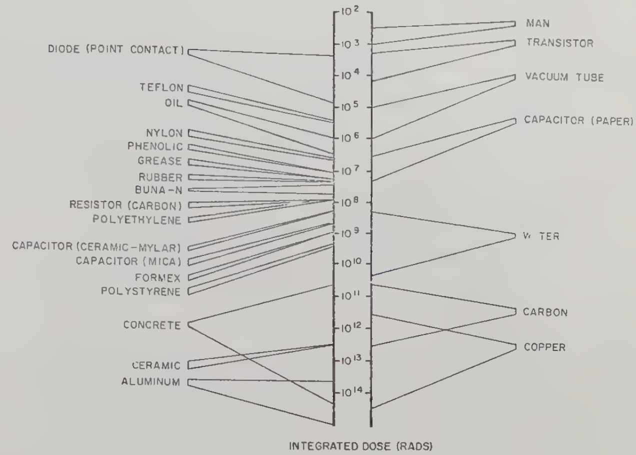


Fig. 13. Functional radiation dose thresholds.

BIBLIOGRAPHY

[1] R. A. Minzer and W. S. Ripley, "The ARDC Model Atmosphere, 1956," AF Cambridge Res. Ctr., ARDC, Bedford, Mass., ASTIA 110233; December, 1956.

[2] H. S. Sicinski, N. W. Spencer, and R. L. Boggis, "Pressure and density measurement through partial pressures of atmospheric component at minimum satellite atmospheres," in "Scientific Uses of Earth Satellites," J. A. Van Allen, Ed., University of Michigan Press, Ann Arbor, pp. 109-118; 1956.

[3] H. K. Kallmann and M. L. Juncosa, "A Preliminary Model Atmosphere Based on Rocket and Satellite Data," The RAND Corp., Santa Monica, Calif., ASTIA AD 207752; October 30, 1958.

[4] R. A. Minzer, K. S. W. Champion, and H. L. Pond, "The ARDC Model Atmosphere, 1959," AF Cambridge Res. Ctr., ARDC, Bedford, Mass.; August, 1959.

[5] E. H. Vestine, "Exploring the atmosphere with a satellite-borne magnetometer," in "Scientific Uses of Earth Satellites," J. A. Van Allen, Ed., University of Michigan Press, Ann Arbor, pp. 198-213; 1956.

[6] S. F. Singer, "Measurements of the earth's magnetic field for a satellite vehicle," in "Scientific Uses of Earth Satellites," J. A. Van Allen, Ed., University of Michigan Press, Ann Arbor, pp. 215-231; 1956.

[7] S. F. Singer, "Rocket exploration of magnetic fields and electric currents in the upper atmosphere," in "Rocket Exploration in the Outer Atmosphere," R. L. F. Boyd and M. S. Seaton, Eds., Pergamon Press, London, Eng.; 1954.

[8] "Space Probes Program Status Report," Space Technology Labs., Los Angeles, Calif., STL/TN-60-0000-02083; April 29, 1960.

[9] M. Dubin, "Meteoric bombardment," in "Scientific Uses of Earth Satellites," J. A. Van Allen, Ed., University of Michigan Press, Ann Arbor, pp. 292-300; 1956.

[10] F. L. Whipple, "Meteorite phenomena and meteorites," in "Physics and Medicine of the Upper Atmosphere," C. S. White and O. O. Benson, Eds., University of New Mexico Press, Albuquerque, pp. 137-170; 1952.

[11] D. B. Beard, "Interplanetary dust distribution and Erkin effects," Proc. 3rd Type Velocity Impact Symp., p. 301; 1950.

[12] R. F. Henderson and P. Stanley, "The Effects of Micrometeorites on Reflectory Surfaces," (paper, no date).

[13] A. M. Mayo, "Basic environmental problems relating man and the aerospace as visualized by the aeronautical engineer," in "Physics and Medicine of the Upper Atmosphere," C. S. White and O. O. Benson, Eds., University of New Mexico Press, Albuquerque, pp. 6-22; 1952.

[14] J. A. Van Allen, "The nature and intensity of cosmic radiation," in "Physics and Medicine of the Upper Atmosphere," C. S. White and O. O. Benson, Eds., University of New Mexico Press, Albuquerque, pp. 239-266; 1952.

[15] J. A. Van Allen, "Cosmic ray observation in earth satellites," in "Scientific Uses of Earth Satellites," J. A. Van Allen, Ed., University of Michigan Press, Ann Arbor, pp. 171-193; 1956.

[16] S. T. Nelson, "A Brief Summary of Cosmic Ray Data with Regard to Space Vehicle Protection," Army Ballistic Missile Agency, Rept. DV-TR-59; April 15, 1959.

[17] "Space Radiation as an Environmental Constituent," Rad. Effects Information Ctr., Batelle Memorial Inst., Columbus, Ohio, REIC Memo 19; January 15, 1960.

[18] B. V. Wacholder and E. Fayer, "Critical Environments Encountered by High Altitude Vehicles," (paper, 1960).

[19] F. S. Johnson, "The solar constant," J. Meteorol., vol. 2, no. 6, p. 431; 1954.

[20] A. Rosen to R. B. Muchmore, "Radiation Environment of Communication Satellite," Space Technology Labs., Los Angeles, Calif., Letter 7430.2-121; December 29, 1959.

[21] Personal conservation with A. Rosen, Space Technology Labs., Los Angeles, Calif., May 26, 1960.

[22] J. A. Van Allen, A. H. Ludwig, E. C. Ray, and C. E. McIlwain, "Some Preliminary Reports of Experiments in Satellites 1958 Alpha and 1958 Gamma," Natl. Acad. of Sciences, Natl. Res. Council, Washington, D. C., IGY Satellite, Rept. Ser. No. 3, pp. 73-92; 1958.

[23] J. A. Van Allen, C. E. McIlwain, and B. H. Ludwig, "Radiation observation with Satellite 1958," J. Geophys. Res., vol. 64, pp. 271-286; 1959.

[24] A. Rosen, C. P. Sonett, and P. J. Coleman, Jr., "Ionizing radiation at altitudes of 3500 to 36,000 kilometers," J. Geophys. Res., vol. 64, pp. 709-712; July, 1959.

[25] J. W. Lindner, "Exploration of the Terrestrial Radiation Belt," Space Technology Labs., Los Angeles, Calif., STL/TR-59-0000-00625; March 10, 1959.

[26] A. Rosen, P. J. Coleman, Jr., and C. P. Sonett, "Ionizing radiation detected by Pioneer II," Planet Space Sci., vol. 1, pp. 343-346; 1959.

[27] J. W. Lindner to R. B. Muchmore, "Background Measurements for Communication Satellite," Space Technology Labs., Los Angeles, Calif., Letter 7320.3-173; December 30, 1959.

[28] A. Rosen, T. A. Farley, and C. P. Sonett, "Soft Radiation Measurements on Explorer VI, Earth Satellite," Space Technology Labs., Los Angeles, Calif.

[29] J. A. Van Allen and L. A. Frank, "Radiation around the earth to a radial distance of 107 km," Nature, vol. 183, p. 430; 1959.

[30] J. A. Van Allen, "Geomagnetically trapped corpuscular radiation," J. Geophys. Res., vol. 69, p. 1683; November, 1959.

[31] S. F. Singer, "The Corpuscular Radiation Environment of the Earth," ASTIA AD 216312; June 18, 1959.

[32] "Materials Problems Associated with Thermal Control of Space Vehicles," Ad Hoc Committee on Thermal Control of Space Vehicles, Natl. Acad. of Sciences, Washington, D. C., Draft Rept. MAB-(); July, 1959.

[33] H. M. Preston and N. E. Wahl, "Influence of Ultraviolet and Vacuum Environments of Structural Plastics," Inst. of Environmental Sciences, Los Angeles, Calif.; April 6-8, 1960.

[34] G. F. Vanderschmidt and J. C. Simons, Jr., "Material sublimation and surface effects in high vacuum," in "Symposium, Surface Effects on Spacecraft Materials," John Wiley and Sons, Inc., New York, N. Y.; 1960.

[35] A. Weissberger, "Physical Methods of Organic Chemistry," Interscience Publishers, Inc., New York, N. Y., vol. 1; 1959.

[36] M. R. Acter, "Effects of high vacuum on mechanical properties," in "Symposium, Surface Effects on Spacecraft Materials," John Wiley and Sons, Inc., New York, N. Y.; 1960.

[37] F. J. Clauss, "Surface Effects on Materials in Near Space," Inst. of Aeronaut. Sciences, San Francisco, Calif.; December 17, 1959.

[38] C. Gazley, W. W. Kellogg, and E. H. Vestine, "Space Vehicle Environment," The RAND Corp., Santa Monica, Calif., Rept. No. P-1335.

[39] R. L. Bjork and C. Gazley, Jr., "Estimated Damage to Space Vehicles by Meteoroids," ASTIA AD 230073; February 20, 1959.

[40] J. J. Hardwood, H. H. Hausney, J. G. Morse, and W. A. Rauch, "Effects of Radiation on Materials," Reinhold Publishing Co., New York, N. Y.; 1958.

[41] J. J. Linnenbom, "Effects of radiation on materials," Insulation; January, February, and March, 1960.

[42] R. L. Plazman, "What is ionizing radiation?" Sci. Am., vol. 201; September, 1959.

[43] F. A. Bovey, "The Effects of Ionizing Radiation on Natural and Synthetic High Polymers," Interscience Publishers, Inc., New York, N. Y.; 1958.

[44] G. J. Dienes and G. H. Vineyar, "Radiation Effects in Solids," Interscience Publishers, Inc., New York, N. Y.; 1957.

[45] D. Pickner, "Radiation damage in metals," Engrg. and Design; January, 1960.

[46] W. C. Riley, W. G. Coppins, and W. H. Duckworth, "The Effect of Nuclear Radiation on Glass," Rad. Effects Information Ctr., Batelle Memorial Inst., Columbus, Ohio, REIC Memo 9; November 30, 1958.

[47] Personal conversations with P. M. Cool, P. W. Wallace, J. B. Meckle, and V. L. Lanza, Raychem Corp., Redwood City, Calif.

[48] J. R. Crittenden, "Nuclear Radiation and Electronic Equipment," GE Co., Cincinnati, Ohio; May, 1959.

[49] S. P. Kaprielyan, "What radiation does to electronic components," Aircraft and Missiles, pp. 18-21; January, 1960.

[50] "Symposium on Radiation Effects on Materials," Am. Soc. for Testing Materials, Philadelphia, Pa., vols. 1-3; 1956-1958.

[51] D. E. Hill, "Electron Bombardment of Silicons," BAPS 1, p. 321; 1956.

[52] F. J. Reid, "The Effect of Nuclear Radiation on Semiconductor Devices," Rad. Effects Information Ctr., Batelle Memorial Inst., Columbus, Ohio, REIC Rept. No. 10; April 30, 1960.

[53] J. M. Denney and D. Pomeroy, "Radiation damage and transistor life in satellites," Proc. IRE (Correspondence), vol. 48, pp. 950-952; May, 1960.

[54] G. C. Huth, "The Effect of Variation of the Width of the Base Region on the Radiation Tolerance of Silicon Diodes," Aircraft Nuclear Propulsion Dept., GE Co., Cincinnati, Ohio.

[55] S. C. Frieden and R. S. White, J. Geophys. Res., vol. 65, p. 1377; May, 1960.

[56] "Satellite Systems Engineering Material Specification," Missiles and Space Div., Lockheed Aircraft Corp., Sunnyvale, Calif., A-MS 3-1020C; April 6, 1960.

Small Subcontractors In Reliability Programs*

DONALD C. BERMAN†, Member, IRE

Summary—Today's military systems contracts invariably have numerical and organizational reliability requirements. With systems of any size, it is advantageous for the prime contractor to subcontract out many equipments and units. Small firms often provide superior specialized technical competence, more favorable prices, faster delivery, and a more conscientious effort; however, the small firm's lack of continuing and repetitive contractual requirements for reliability usually results in organizational weakness in this area. These firms are unable to support the cost of permanent reliability, standards, and quality control functions of the type required by these contracts.

A standard comprehensive quality or reliability survey would eliminate these organizations from competition, and a superficial survey leading to their acceptance would result in the acquisition of an ineffective subcontractor. As a substitute, a specially designed analytical survey is performed which investigates the quality, reliability, standards, and design functions of the prospective subcontractor, and indicates not only the deficiencies, but also the remedial action required.

If, on the basis of price, delivery and technical competence, a firm in this category is awarded a subcontract, procedures are instituted which invariably result in a reliability achievement at least equal to that of some large organizations which, at times, have inflexible and incompatible procedures.

This paper describes, in brief, the survey techniques and the remedial procedures instituted.

Today's military systems contracts invariably have numerical and organizational reliability requirements. When the military selects a prime contractor for a system contract with such requirements, it usually chooses from among a group of organizations who already have the required reliability functions established to some extent. With systems of any size, however, it is advantageous for the prime contractor to subcontract out many equipments and units. Small firms often provide superior specialized technical competence, more favorable prices, faster delivery, and a more conscientious effort.

Typically, you receive much better service from a small company that regards you as the "golden goose," than you do from a large one to whom you represent but a fractional per cent of sales. Unfortunately, however, the small firm's lack of continuing and repetitive contractual requirements for reliability, usually results in organizational weakness in this area. These firms are unable to support the cost of permanent reliability, standards, and quality control functions of the type required by these contracts, and quite often cannot even generate the impressive manuals needed to establish fictitious paper functions. Being aware of this situation, the prime contractor has three choices when planning a "vendor survey" of these organizations; they are to:

1) Conduct a comprehensive survey and, as a result of the low score achieved, disqualify the small firm as a subcontractor.
2) Conduct a superficial survey and qualify the firm.
3) Conduct a comprehensive survey which not only reveals the deficiencies in the reliability, standards, and quality control functions of the firm, but also indicates the necessary remedial action.

At Fairchild Astrionics Division the third type of survey is employed. Should this survey indicate that a firm has both a genuine desire to meet our contractual reliability requirements, and the capability for producing a quality product, they are approved conditionally. If, on the basis of all pertinent considerations, a firm in this category is awarded a subcontract, procedures are instituted which invariably result in a reliability achievement equal to or better than that of many large organizations who can conceivably have inflexible, incompatible, or inadequate methods. The result of this program is that technically superior equipment, of the required reliability, is delivered at a low cost, in short time, accompanied by the desired reliability data.

As mentioned previously, there are several general types of vendor surveys that can be made by a quality or reliability section. The number of

*This paper was presented at the third meeting of the Long Island Reliability Forum, Huntington, L. I., N. Y., September 20, 1960.

† Fairchild Astrionics Div., Fairchild Engine and Airplane Corp., Wyandanch, L. I., N. Y.

questions, scoring, and depth of probing vary from company to company. One example of a thorough reliability survey is the Bell Aircraft check list, found in Air Force Specification Bulletin 510. The list covers 23 pages and consists of 250 questions; and the organizations that can make even passable scores are few and far between. Were we to utilize a survey check list such as this, our roster of acceptable subcontractors would be severely limited. An example of a thorough quality control survey is the ITT Federal survey. This covers 22 pages and consists of over 270 questions. A large organization, with good "old line" quality control established for the manufacturing facility, has a good chance of passing this.

If you allot one day apiece for each of the two surveys mentioned, arrive at 9:00 and leave at 5:00 each day, do not go out for lunch, and never leave the office of the QC manager during the day, you can usually complete these surveys. The disadvantages, other than missing lunch, are obvious. These surveys have everything in the book thrown in, and only by relying on the QC manager for all information, and by assuming that their QC and reliability manuals are completely up to date, can you complete the survey even in two days.

Of course there is an easy out—one used by many companies. This is the "short form." It enables the surveyor to arrive at ten, tour the plant; go to lunch from 12:00 to 2:30, and leave for home at 3:00. This type of survey has found widespread popularity. To simplify the survey process, it is very often left with the vendor so that he may complete it at his leisure and forward it to the surveying organization. A typical example in my possession covers three pages and has 35 questions, most of which can be completed by Yes or No.

At this point we have something of a dilemma—we don't want to be superficial, nor do we have the days required for extremely detailed surveys; yet we would like to use small vendors. To this end, we have designed a survey based on the principle that we are interested in a vendor's capability of performing in an R and D contract when his organization is complemented and assisted by ours. For each question in the survey form, the surveyor may be asked to check a rating of either 0, 1, 3, or 5; check "Seen," indicating that he has actually seen the referenced item in use; check "attached" indicating that a particular form is attached; and, where appropriate, make comments. The survey has 121 questions divided among the following areas:

1) Quality control
2) Reliability
3) Inspection
4) Standards
5) Instrument maintenance
6) Environmental facility
7) Failure control
8) Vendor control
9) Drawing control
10) Environmental design competence.

To be done correctly, the surveyor should be on the move continually, and the emphasis is on checking what the vendor is actually capable of doing himself. As an example, the first question under failure control is, "Are reports submitted on failures which occur during assembly and wiring?" To find out, we don't ask the QC manager whether he complies and then take his word for it. We don't look in the QC manual and accept the report form we see there as proof. We don't look at the blank form he brings in and accept it as proof. We don't look at the filled-out form he brings in and accept it as proof. What we do is to follow him to a filing cabinet, look in a drawer, and, if we see filled-out forms for the past three months, they are accepted as proof.

To sum up the discussion on surveys, the survey must clearly show:

1) What the vendor actually does.
2) What he is aware needs doing.
3) What he needs help in doing.

If the vendor is performing a reasonable quality effort for an organization of his size, if he is aware of what he should be doing were funds and personnel available, and if the interest in reliability is there, the vendor will be approved.

Once an organization without a full-fledged active reliability function is approved as a vendor, we follow through with procedures designed to make the vendor a useful member of the system team. In a sense, we treat the vendor as if he were a design group in our organization. It must be realized, though, that the procedures which we use are not compatible with the philosophies of many companies who feel that a service group should supply information only when requested. Operating under that philosophy, the reliability group is in a position of having to censure repeatedly what has already been designed. We believe that if the reliability, standards, and quality groups set forth guidelines before the design engineers perform their work, they will be viewed as true service groups, not censure groups. Most engineers are genuinely appreciative when preferred parts, pertinent processes, application notes, environmental notes, and reliability guides are provided to them early enough to guide them, not censure them. When these concepts are introduced later, only hostility will result.

This leads us to Procedure One: "Supply

preferred parts lists, standards, and application information at the initial phase of the contract." At FAD, we have a preferred parts list from which 90 per cent of the circuit components can generally be selected. The vendor, though, is not restricted to this list any more than our own engineers are. By using this list, the subcontractor is relieved of the necessity of supplying many nonstandard part data sheets or submissions, of evaluating sources, of providing application information, and of preparing procurement drawings. The columnar headings for resistors in this list, and the entries for one type are shown below:

Description Resistor, Fixed Carbon Film $\pm$ 1 per cent
MIL/FAD No. RSF 102 (RN60 B Type)
Stability in PPM °/c $\pm$500
Max. Working Voltage 250 vdc
Max. Wattage at 55,000 ft°: 70° C = 0.09; 85° C = 0.08; 100° C = 0.06
Resistance Range in Ohms 5-1.0 meg
Max. Length 0.438
Max. Diameter 0.165
0.100 Grid Mtg. Centers 0.700
Preferred Manufacturer Mepco F170H
Referenced FAD Dwg. RSF 102.

In addition to the preferred parts list, we supply: reliability reference lists, reliability and environmental guidelines, process drawings, component mounting procedures, standard design manuals, individual drawings, and failure-reporting procedures and forms.

Procedure Two is to "Encourage them to call upon our Reliability and Standards personnel for guidance and information." The effectiveness of this procedure is tempered by the distance between plants, and this is a factor in the selection of vendors needing this service. We prefer to have vendors requiring frequent liaison within an hour's flying time or three hours train or car time of our plant.

Procedure Three is to "Perform the reliability or failure rate analysis and the statistical computations for them." Statistical computations of failures are mechanical in nature and are routinely absorbed by the statistical coordinator at FAD. The time required to process the data of any one subcontractor is minimal, yet if we did not do it, most of our subcontractors would be required to hire statisticians and computer time for only minutes of work per day. The reliability failure rate analysis falls into the same category. Each subcontractor would be required to hire a reliability engineer if he did not already have one. Instead, we have the subcontractor supply for the design reviews a "Reliability Analysis Sheet."

The data required on the Reliability Analysis sheet are divided into three areas: "Parts List," "Application Data," and "Reliability Data." The subcontractor furnishes only the information required in the first two areas; our Reliability personnel perform the mechanical insertion and computation of failure rates. In the "Parts List" columns, we have: Circuit Symbol, Part Number, and Part Family Name. In the "Application Data" columns, we have: operating voltage or wattage; M, E, or C, indicating whether this is measured, estimated, or calculated; rated voltage or wattage; stress factor ratio; operating temperature; M, E, or C, indicating whether this is measured, estimated, or calculated; and number of parts used.

None of the information supplied in these first 10 columns requires a reliability engineer or reliability funding. The parts list columns can be filled out by a clerk, the application data by a technician. For the more complex components, instruction sheets show how to obtain the stress levels, indicating for example, that in electron tubes we define wattage as total tube wattage including that of the heater. The last five columns on "Reliability Data" can for the most part, be completed by an engineering aide trained in the use of TR-58-111, the "RADC Reliability Notebook."(1) This is done at our plant under the supervision of a Reliability Engineer. In the columns, we have: Part Failure Rate in per cent per 1000 hours. Total Failure Rate in per cent per 1000 hours, X if a nonpreferred part, X if a nonstandard part, and Failure Rate Data Source.

Procedure Four is to "Conduct periodic design reviews at their plant." The procedure established for the vendor reviews is nearly identical with that established internally at FAD and is similar to that used by other organizations. It requires a minimum of written preparation on the part of the vendor, with the exception of the Reliability Analysis sheet. The three types of reviews normally employed are: a concept review held prior to award of the contract, a schematic review prior to schematic release, and a packaging review prior to detail drawings.

Procedure Five is to "Schedule periodic liaison by our Reliability and Project personnel." This effort is limited by the vendor's accessibility from our plant. The actual frequency of visitations, though, is dictated by the vendor's performance.

In summation: A prime contractor subcontracts out work because his manpower limitations

[1] J. J. Naresky, "RADC Reliability Notebook," Rome Air Dev. Ctr., Griffis AFB, Rome, N. Y., RADC-TR-58-111, ASTIA AD-148868, Govt. Printing Office PB-161894.

makes it impossible to fulfill schedule obligations, or because specialized design competence exists elsewhere. For a given system contract, it takes only one standards group to prepare the necessary preferred parts lists and standards. It takes only one reliability group to prepare procedures, assign failure rates, and compute probability of survival. It takes only one statistical group to prepare statistical data. If the service functions exist as overhead at his subcontractors, well and good, but since both the prime and subs are working on the same system, there is no need to duplicate direct labor service functions. When your own procedures, standards, and forms are utilized, the result is predictable. Vendors with established procedures in these areas are often inflexible, and can be extremely difficult to work with.

The average small subcontractor can participate effectively in reliability programs, and the absence of reliability, standards, and statistical functions in his organization is, with proper supervision, not a liability, but instead, a potentially strong asset.

The Economics and Reliability of Multifunction Devices*

J. A. DAVIES† and C. D. MCCOOL†, Senior Member, IRE

Summary—The widely prevalent assumption that device failure rates are multiplied when two or more functions are incorporated in a single enclosure is examined with respect to actual experience on single-element vs multiple-element electron tubes. The feasibility and economics of multi-element structures are considered in the light of the recent trend toward greater and greater complexity of device combinations. The natural limits to this trend are predicted by extrapolating known factors related to spread of characteristics, random catastrophic failures, and life. Some of the most recent examples of this philosophy are described and discussed in comparison to earlier versions providing similar functional performance.

SECTION I: FEATURES OF COMPACTRON MULTIFUNCTION DEVICES

Our subject deals with a very recent development in the field of vacuum-type receiving tubes, so we feel that it would be helpful to present first a brief description of the device from a design standpoint. The component under discussion is the Compactron, a thermionic vacuum device designed to do the work of several electronic receiving tubes or transistors in home radios, auto radios, television, hi-fidelity tuners and amplifiers, electronic organs, and a variety of other commercial and industrial equipments. Multifunction vacuum tubes are not exactly new in our business and several types such as the 6T8, 6EZ8 and 6BW8 shown in Fig. 1 have been used successfully for a number of years. The Compactron has carried the multifunction concept one step further, and it is our belief that it will offer equipment manufacturers not only savings in both space and cost, but also improved reliability.

In a home radio, for instance, two Compactrons (Fig. 2) may replace five conventional receiving tubes or seven transistors; or in the higher price lines, three Compactrons can easily replace six

Fig. 1. Types 6T8, 6EZ8 and 6BW8 multifunction 9-pin miniature tubes.

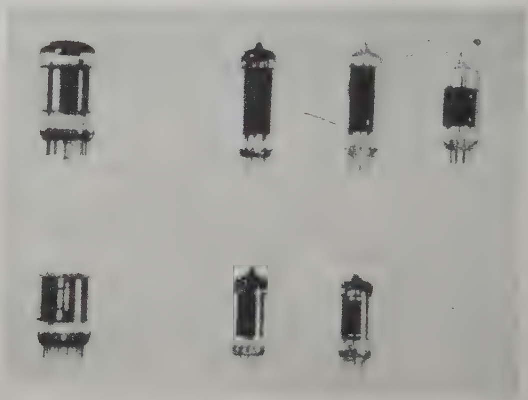


Fig. 2. Two Compactron multifunction devices (left) which perform the functions of five conventional miniature tubes in home radios.

conventional tubes or eight transistors. In Fig. 3 is shown a sample of a 2-Compactron home radio which was put together by our engineers to demonstrate one application of the Compactron concept. This little radio, which has a rather low, modern silhouette, is the equivalent of a conventional five-tube or seven-transistor set and has a power output of 1 watt at 10 per cent distortion and a sensitivity of 67 μv per meter for 50 mw output. The Receiving Tube Department of General Electric is not in the business of manufacturing radios, so you will not see this particular model on the market, but many of our customers are actively working on Compactronized designs of radio and television receivers.

In terms of its distinctive design features the Compactron is contained in a compact, bottom-exhausted envelope with 12 electrical connections (Fig. 4). The 12 pins are adequate to take care

*This paper was presented at the Fall Radio Meeting, IRE and Electronic Industries Association, Syracuse, N. Y., November 2, 1960.

†Receiving Tube Dept., General Electric Co., Owensboro, Ky.

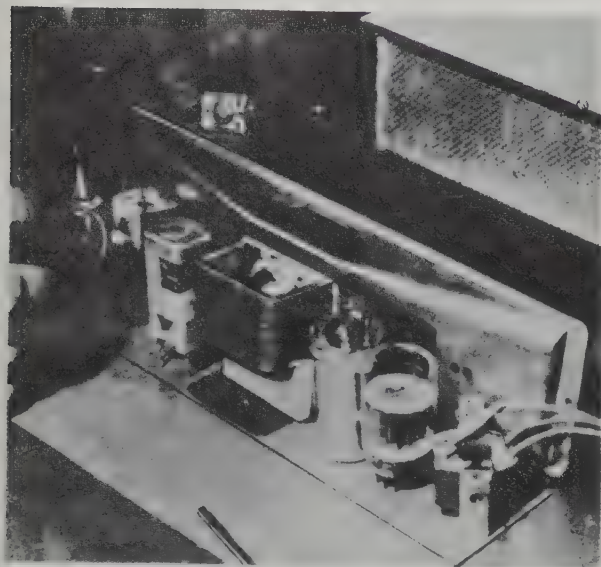


Fig. 3. Mechanical mock-up of a 2-Compactron radio chassis and cabinet.

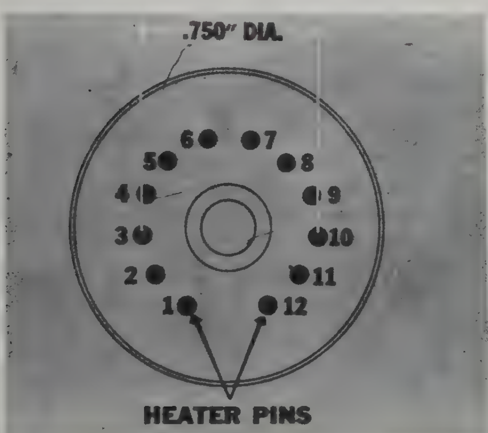


Fig. 4. New 12-pin base for Compactron devices, with pins spaced on a 0.750-inch circle.

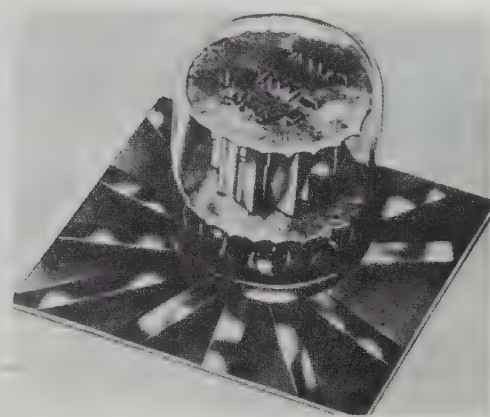


Fig. 5. Illustration of a Compactron device plugged directly into a printed circuit board, with pin clips soldered to the board.

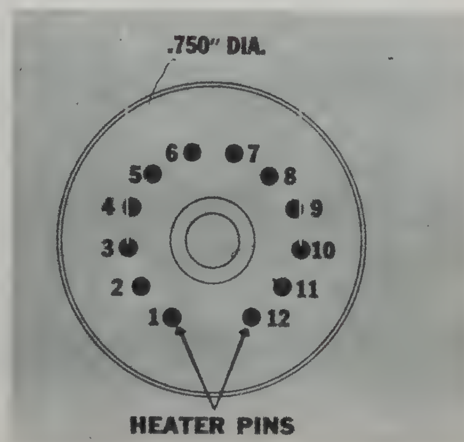


Fig. 6. Standard heater pin connections to pins 1 and 12 of the new base.

of most multifunction structures for television, radio and hi-fi circuits, and the pins are spaced far enough apart to meet requirements of electrical performance and construction economics.

From the equipment manufacturers' point of view, the 12-pin design offers savings in assembly costs. It adapts well to printed circuitry (Fig. 5) in that the large pin circle provides adequate space to make connections to all of the pins. By locating the heater on pins 1 and 12 (Fig. 6), additional space is available to bring a heavier printed circuit into the heater leads if this is necessary to carry higher currents.

There are several structural advantages gained from the 12-pin circle. It provides a very firm foundation for the internal structures of the Compactron (Fig. 7). For the most part, the pin circle is such that points of support fall directly under the electrodes to which they are attached. Welding of the inner pin connections is simplified by comparison with conventional miniature tubes. With the additional spacing between pins, spot-welding points are easier to reach, thus assuring reliable connections and at the same time facilitating automatic assembly methods.

Aside from purely structural considerations, several desirable electrical features are also obtained with the Compaction. By locating the plate on one pin and allowing two unused pins on either side, we can get a voltage isolation in the order

Fig. 7. View of a typical multifunction device showing firm support for the internal structure.

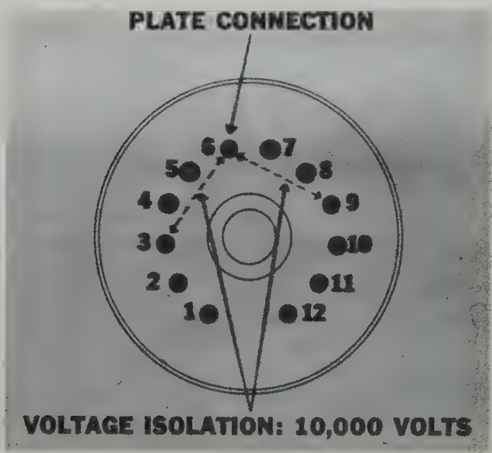


Fig. 8. Diagram of the 10,000-volt isolation capability of the new 12-pin base with two blank pins between active pins.

of 10,000 volts (Fig. 8). This is a good 50 per cent greater than the maximum peak voltage encountered in horizontal deflection circuits of television receivers. This margin of safety permits the design of single-ended devices for horizontal deflection service, thus offering considerable additional savings to the set designer in that the top cap connector and adaptor can be eliminated. A related advantage is the fact that we can minimize glass electrolysis, which may occur in conventional tubes as a result of extended periods of high temperature and high voltage, and can lead to actual cracks or leaks in the tube. The wider spacing of Compactron pins significantly reduces this possibility.

When you look at tube size from the standpoint of the man who is going to design a television or radio receiver, the distance from the base to the top of the tube is usually an important feature. When standard miniature tubes are used, the designer has to provide height in the cabinet to clear the exhaust tip which is usually about 5/16 inch long (Fig. 9). What we have done in the

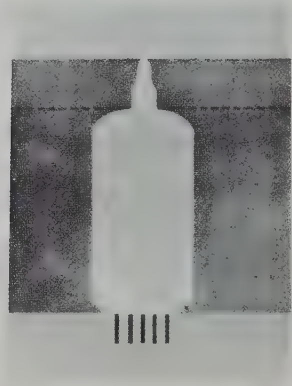


Fig. 9. Outline view of a conventional miniature tube with a seal-off tip at the top of the envelope.

Compactron is take the exhaust tip off the top and put it between the pins on the bottom so that the envelope space is fully utilized (Fig. 10).

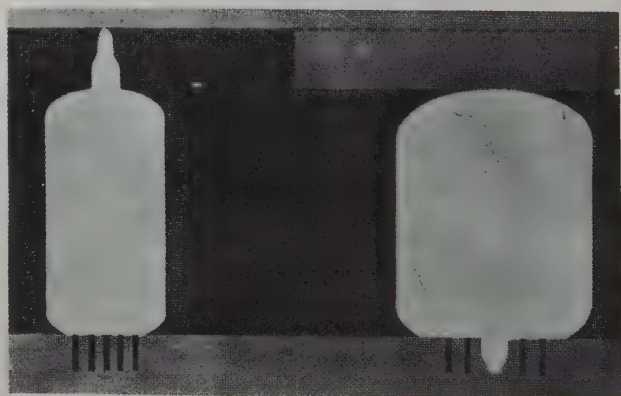


Fig. 10. Vertical space saved by moving the seal-off tip to the base of the new multifunction device.

A 1 1/8-inch-diameter (T-9) bulb was selected to allow enough space to package multifunction structures (Fig. 11). With the shorter Compactrons, the height of this space will be approximately the same as its diameter. The T-9 envelope offers enough bulb area to dissipate adequately the power required for most amplifier and deflection circuits. In applications where

Fig. 11. Outline of a multifunction envelope 1 1/8 inch in diameter.

unusually high power and voltage ratings are required, we intend to use a 1 1/2-inch-diameter (T-12) bulb (Fig. 12). Applications such as these,

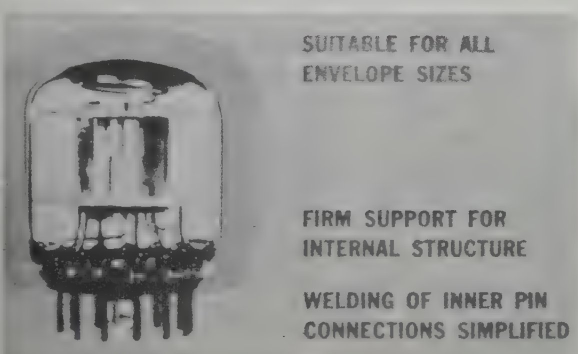


Fig. 12. The multifunction device in the T-9 1 1/8-inch-diameter envelope with outline of T-12 outline 1 9/16 inch in diameter.

however, will remain single-function. This includes some horizontal deflection amplifiers, audio power amplifiers and power rectifiers.

The T-9 (1 1/8-inch-diameter) bulb will also allow us to mount a structure horizontally, permitting wide flexibility in design and offering certain manufacturing advantages. As you can see from Fig. 13, this approach lends itself well to automatic assembly which again contributes to uniformity in manufacturing.

Now let's take a look at the reliability features of the Compactron structure. Fig. 14 shows one of the home radio Compactrons, a diode-triode-pentode rectifier. The functions are detector-audio amplifier, audio power output amplifer and rectifier. By combining three tube functions as in this example, along with a double-function pentode-heptode to serve as IF amplifier and oscillator-

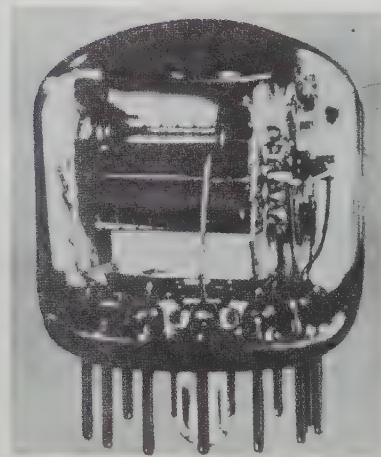


Fig. 13. Horizontal mounted internal cage structure of the multifunction device permits short, direct connections to base pins.

Fig. 14. A multifunction device for home radio combining detector, audio voltage amplifier, audio power amplifier and power rectifier stages in one envelope.

mixer, we achieve a 2-Compactron home radio complement (Fig. 15) that provides a considerable reduction in the number of parts and welds subject to defects, as compared to the 5-tube kit.

In addition to a reduction of component parts, many Compactron designs will employ an integral heater (Fig. 16), which will supply power for as many as three separate cathodes. The three-cathode integral heater requires only two welds. In comparison with conventional single-function designs, this eliminates four heater welds, thus reducing production costs and providing inherently greater reliability in the device.

The larger bulb area obtained in most Compactron designs serves to keep the temperature of the glass relatively low, thus contributing to better life. Below are some typical examples of

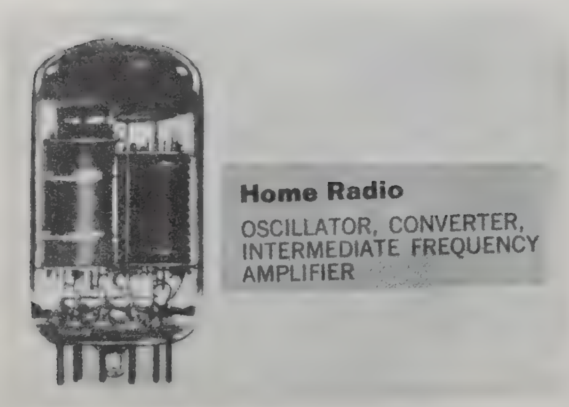


Fig. 15. A multifunction device for home radio combining converter, oscillator and IF amplifier functions into one envelope.

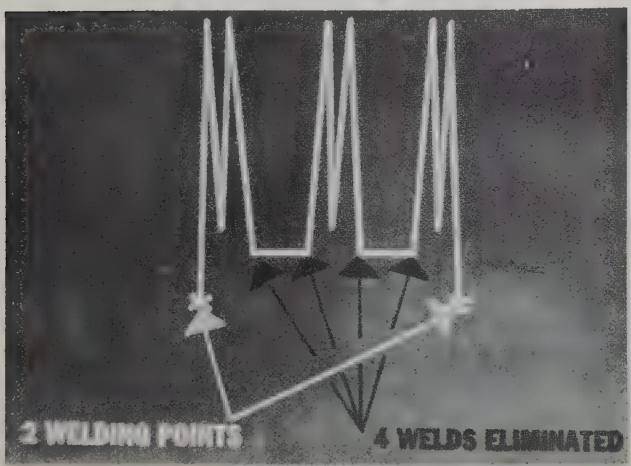


Fig. 16. Integral series heater for a three-section multifunction device made from a single length of heater wire.

average bulb temperature of several Compactron types and their conventional miniature counterparts. These measurements were taken at maximum rated dissipations, and represent a part of the data used in this paper to evaluate life test failure rates as a function of bulb temperature. (See table at top of next column.)

Failure rates resulting from wear-out or degradation of electrical characteristics are expected to be the same for Compactron devices as for the combined individual units performing the same functions. However, experience with television and radio life tests show that the number of such failures during the 1500 hours covered by these tests is much smaller than the number of inoperative failures. Deterioration due to stress at or

COMPACTRON		CONVENTIONAL TUBE EQUIVALENT		
Duplex diode Triode Pentode	165°C	18FY6 32ET5 36AM3	- - -	65°C 165°C 105°C
Heptode Pentode	105°C	18FX6 18FW6	- -	80°C 110°C
Twin Diode Triode Pentode	137°C	6AL5 6GH8	- -	50°C 177°C
Triple Triode -	132°C	12AT7 6AB 4	- -	142°C 104°C
Twin Diode Twin Triode	117°C	6AL5 6CG7	- -	50°C 167°C

Ambient temperature 28°C

near maximum ratings would go on concurrently, as, for instance, in the audio output and rectifier sections. This would not increase the probability of failure from these causes at all.

Finally, multifunction devices will for the most part do the easier jobs in radio and television circuits. All of the functions in a home radio are relatively easy on the tube compared to some of the well-known "problem" sockets in television, such as the horizontal and vertical deflection amplifier. In these sockets, where high dissipations, high temperatures, and high voltages are usually involved, single-function types will probably continue to be used.

SECTION II: RELIABILITY, TEMPERATURE AND COST FACTORS OF MULTIFUNCTION DEVICES

Estimating Reliability

Estimates of the expected reliability of Compactrons were made by using actual life test data for failure rates together with theoretical factors based on relative structures and bulb temperatures. The resulting estimate, expressed in terms of failure rate, is given by the following simplified form

$$FR_c = (\Sigma FR) \times S \times T \qquad (1)$$

where

FR_c = the estimated failure rate of the Compactron

(ΣFR) = the summation of actual failure rates of the combined prototypes
S = the structure factor
T = the temperature factor.

The factor (ΣFR) was obtained from life test data on the prototype tubes, operated under maximum rated conditions for 500 to 1000 hours. These results were compared with corresponding failure rates obtained from radio and television set life tests at various line voltages up to 107 per cent of nominal. Two conclusions were drawn.

1) Failure rates for both inoperatives and electrical defects on tube life tests are 2 to 3 times those on set life tests.
2) Degradation rates of electrical characteristics are quite low on both life tests, so the contributions of electrical failures to the total is not significant and may be omitted.

Consequently, the structure and temperature factors were developed on the basis of inoperatives only. Electrical degradation of Compactrons will not exceed that of the prototypes, and in fact, it is expected to be slightly less due to reduced temperature of operation.

Structure Factor

The structure factor is the relative proportion of inoperatives expected due to the Compactron structure. It is based on a two-fold classification of inoperatives from the life test study into groups either related to or independent of the structural differences between Compactrons and their prototypes. A further subclassification of the "related to" group identified each tube failure with one of five structural items: heater, welds, stems, bulb, or pins. The number of defectives in each part of the classifications provided a means for assigning empirical weights in the derived equation. Thus, we define:

d_1 = that group of inoperatives whose probability of occurrence, P_1, is equally present in both tube and Compactron structures. This type of defective is illustrated by H-K failures, element shorts, and cathode defects.

d_2 = that group of inoperatives whose probability of occurrence, P_2, is variable due to the relative number of structural items. This type is illustrated by open heaters, defects due to heater coating, open welds, gas, air, missing or broken pins, and glass cracks.

Hence, the structure factor is

$$S = \frac{d_1P_1 + d_2P_2}{d_1 + d_2} = W_1P_1 + W_2P_2 \qquad (2)$$

where

$$W_1 = \frac{d_1}{d_1 + d_2}, \quad W_2 = \frac{d_2}{d_1 + d_2}$$

P_1 = 1 by previous definition

$P_2 = \Sigma W_S R_S$, the weighted sum of the structural ratios.

Using the empirical weights, we obtain

$$S = 0.38 + 0.62P_2 \qquad (3)$$

where P_2 is given by

$$P_2 = 0.50R_h + 0.125\,(R_w + R_s + R_b + R_p) \qquad (4)$$

and the R's are ratios of the number of heaters, welds, stems, bulbs, and pins in Compactrons compared to the combined prototypes.

For example, a Compactron which combines the diode structures of a duplex-diode pentode with a triode-pentode is compared with the combined prototypes, 6BW8 and 6GH8.

Structural Items	Compactron Structure	Prototypes Structure	Ratio R	Weight W	WR
Heaters	1	2	1/2	0.5	0.25
Welds	17	24	17/24	0.125	0.0885
Stems	1	2	1/2	0.125	0.0625
Bulbs	1	2	1/2	0.125	0.0625
Pins	12	18	12/18	0.125	0.0833
				P_2 =	0.5468

Structure Factor: S = 0.38 + 0.62 (0.5468) = 0.719.

Temperature Factor

The temperature factor is a ratio of the estimated per cent of inoperatives for the Compactron and its prototypes, based on bulb temperature. These estimates can be made readily by using the graph of Fig. 1, inoperatives vs bulb temperature

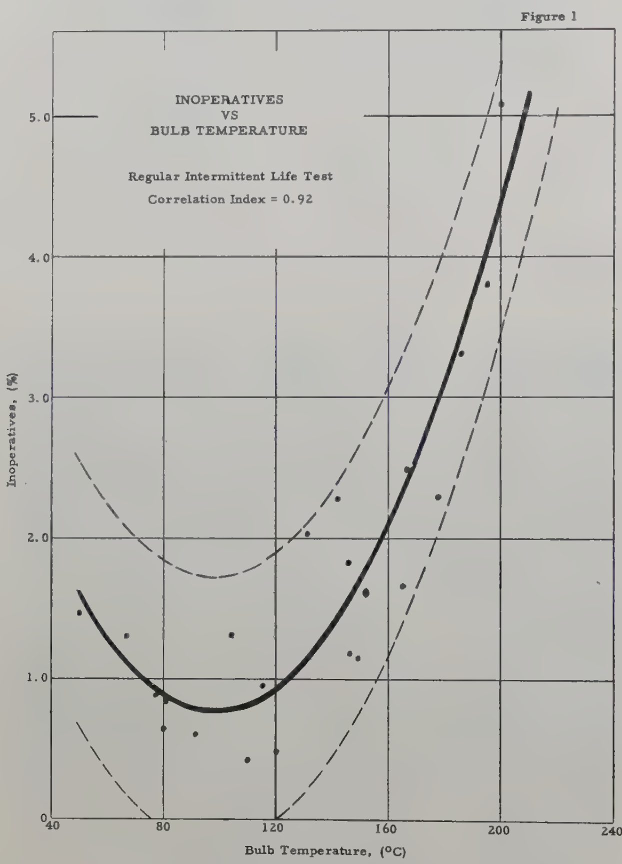


Fig. 1. Inoperatives vs bulb temperature, regular intermittent life test. Correlation index = 0.92.

on regular life test. This graph shows a quadratic relation between inoperatives and bulb temperature. The 95 per cent confidence limits about the regression line are shown. The curve was determined by fitting linear, quadratic, and cubic equations by least squares to 18 points of inoperatives and bulb temperature for multifunction types and prototypes. The quadratic curve gave the best fit, having an index of correlation of 0.92 and standard error of estimate approximately 0.4 per cent inoperatives. Thus, the temperature factor is expressed as

$$T = \hat{d}_c/\hat{d}_p \tag{5}$$

where

$\hat{d}_c$ = the estimated inoperatives (per cent) for Compactrons

$\hat{d}_p$ = the estimates inoperatives (per cent) for prototypes.

Further, the estimates are related to bulb temperature by

$$\hat{d}_c = At_c^2 + Bt_c + C, \tag{6}$$

where t_c = Compactron bulb temperature in °C, and

$$\hat{d}_p = At_p^2 + Bt_p + C,$$

where t_p = prototypes bulb temperature in °C.

Values of the constants are

$A = 0.000353, \quad B = -0.0695, \quad C = 4.20.$

Variance analysis showed that both the bulb size and total dissipation have significant effects on bulb temperature. Hence, curves of bulb temperature vs total dissipation were fitted

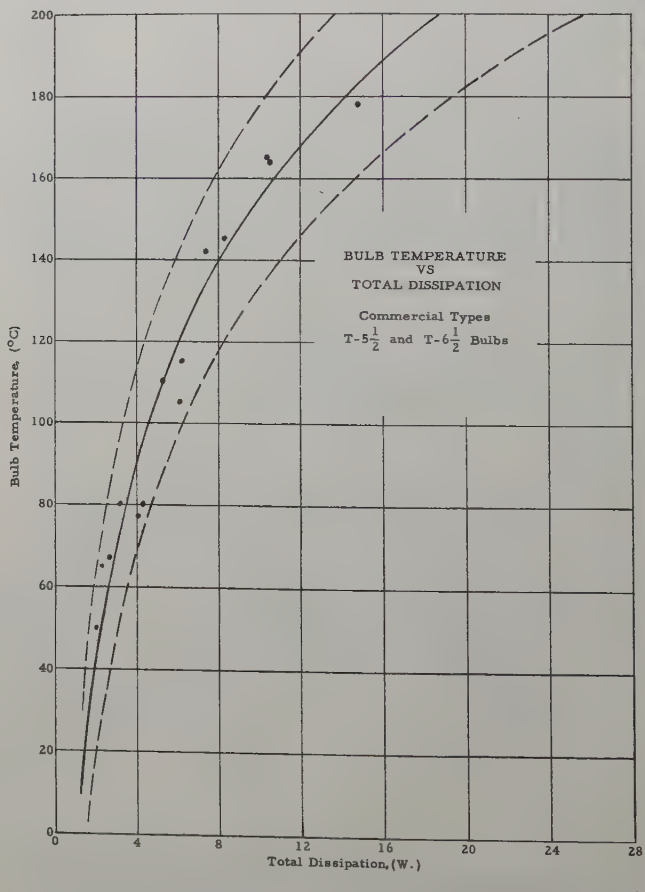


Fig. 2. Bulb temperature vs total dissipation. Commercial types, T-5 1/2 and T-6 1/2 bulbs.

separately for 17 prototypes in T-5 1/2 and T-6 1/2 bulbs, Fig. 2, and for 9 Compactrons in T-9 bulbs,

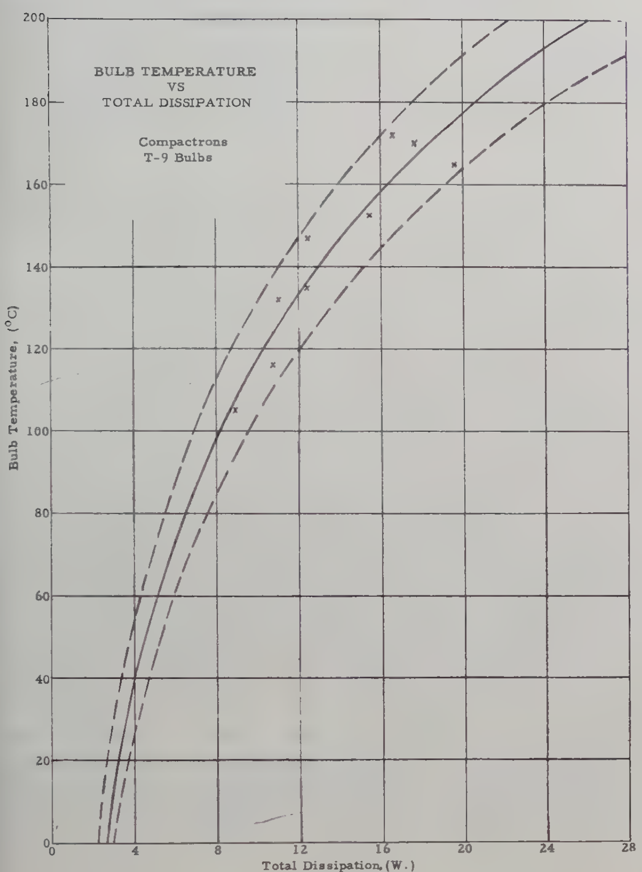


Fig. 3. Bulb temperature vs total dissipation. Compactrons, T-9 bulbs.

Fig. 3. This curve-fitting by least squares gave excellent estimates as follows:

$$t_c = 199 \log w_c - 81.5, \tag{7}$$

where w_c = Compactron total dissipation in watts, and

$$t_p = 163 \log w_p - 7.6,$$

where w_p = prototypes total dissipation in watts.

The indexes of correlation for these two curves are 0.94 and 0.96, respectively, after adjusting downward due to sample size and number of parameters fitted. Standard errors of estimate are 7.1°C and 11.4°C, respectively.

These curves are used to determine the temperature factor as follows:

1) Use the actual total dissipation to estimate the bulb temperature for the Compactron from its curve and the bulb temperature for each prototype separately from its curve (Fig. 4).
2) Use this estimated bulb temperature to estimate inoperatives for the Compactron and similarly for each prototype, using the same curve of inoperatives vs bulb temperature.
3) Total the estimated inoperatives for the prototypes.
4) Divide this total into the estimated inoperatives for the Compactron.

This method is illustrated by the following example for the heptodepentode Compactron whose prototypes are 18FX6 and 18FW6.

		Compactron	18FX6	18FW6	Total
Total dissipation in watts (actual):	w =	9.0	3.15	5.25	(8.40)
Bulb temperature, °C estimated from disspitation:	t =	108	75	110	(143)
Inoperatives, per cent estimated from bulb temperature:	$\hat{d}$ =	0.80	0.96	0.82	1.78 (1.48)

Temperature factor:

$$T = 0.80/1.78 = 0.45$$

Alternate method:

$$T = 0.80/1.48 = 0.54.$$

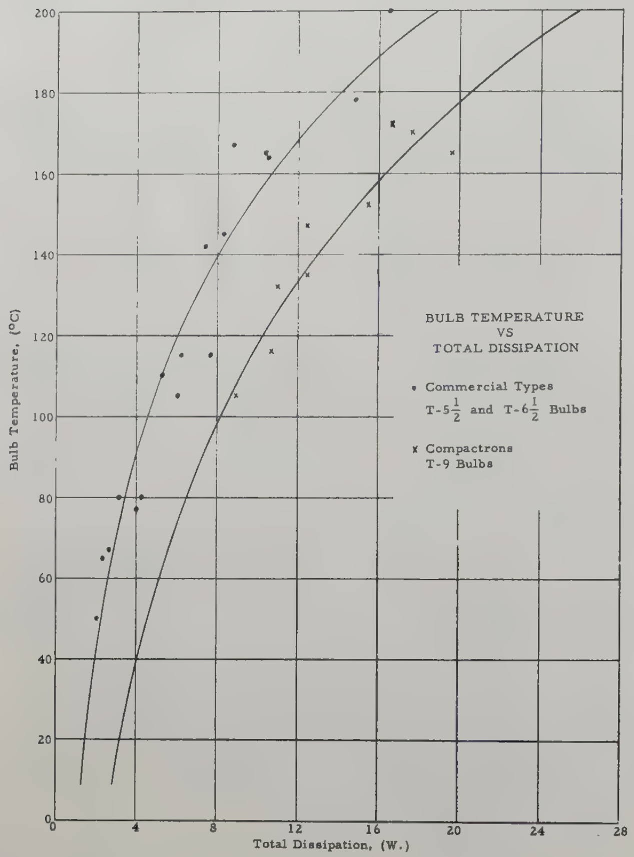


Fig. 4. Bulb temperature vs total dissipation. Commercial types, T-5 1/2 and T-6 1/2 bulbs, indicated by dots. Compactrons, T-9 bulbs, indicated by x's.

Note the figures in parentheses. These figures illustrate an alternate way of making the estimates by combining the total dissipations of the prototypes first. This method gives estimates that are comparable to those of the former method within limits of expected variation. However, the alternate method is artificial since it has no physical counterpart.

It should be noted that a rough estimate of Compactron failure rate can be obtained directly from the Compactron bulb temperature or total dissipation without considering the prototypes. Of course, this procedure does not adjust for prototype structure and other differences. Since the relationship between bulb temperature and inoperatives has an index of correlation of 0.92, then 0.92^2 or approximately 85 per cent of the variation in per cent inoperatives is explained by bulb temperature. This leaves 15 per cent unexplained variation due to all other variables. The ratio method corrects for the unexplained variation equally in obtaining the factor T to adjust for total dissipation and bulb size. Then this factor is used as a multiplier of the actual failure rates of the prototypes. In addition, the structure factor S is needed to account for the difference in the number of structural items.

The following table shows actual values of total dissipation and bulb temperature for a representative group of seven Compactrons and their prototypes.

Compactron Type	Total Dissipation watts	Bulb Temperature °C
1) Duplex-diode Triode Pentode	19.96	165
2) Duplex-diode Triode Pentode	19.96	165
3) Heptode Pentode	9.00	105
4) Heptode Pentode	9.00	105
5) Double Pentode	15.54	152
6) Triple Triode	11.09	132
7) Twin Diode Twin Triode	10.77	117

Conventional Prototypes Type	Total Dissipation watts	Bulb Temperature °C
35W4	7.75	115
50C5	16.50	200
12AV6	2.70	67
36AM3	6.10	105
32ET5	10.45	165
18FY6	2.32	65
12BE6	4.09	77
12BA6	4.99	126
18FX6	3.15	80
18FW6	5.25	110
6CU5	14.81	178
6DT6	4.39	80
12AT7	7.39	142
6AB4	4.80	104
6AL5	2.07	50
6CG7	8.78	167

Finally, a summary of structure factors, temperature factors, and estimated failure rates for this same group of Compactrons is developed using the methods described.

Compactron #	Actual (ΣFR)	Structure Factor, S	Temperature Factor, T *Reg.	Temperature Factor, T Alt.	Estimated FR_c	Ratio to Prototypes Per Cent
1.	6.98	0.84	0.47	0.46	2.75	39
2.	4.21	0.84	0.66	0.67	2.33	55
3.	2.05	0.89	0.50	0.48	0.91	44
4.	1.26	0.89	0.45	0.54	0.50	40
5.	2.93	0.74	0.47	0.42	1.02	35
6.	3.04	0.73	0.53	0.41	1.18	39
7.	4.04	0.72	0.31	0.46	0.90	22

*Used in calculation of estimated FR_c and ratio to prototypes.

Hence, failure rates of Compactrons (including several others not shown above) are estimated to be about 25 per cent to 65 per cent of the combined failure rates of their conventional prototypes. This conclusion is important to considerations of both reliability and economy.

Cost Considerations

Cost considerations will always be of prime importance to the customer. Previously, it was felt that the higher replacement cost of multi-unit Compactron devices, as compared with single-unit tubes, might mean higher over-all costs for the customer—even though the equipment failure rates are reduced by the use of Compactron complements. These present estimates show that actually the initial cost will be slightly lower and the cost of replacements also less for the Compactron complement.

Final prices have not been established for Compactrons as yet, so let's take an hypothetical case for cost comparisons. Cost figures are expressed by index numbers using the cost of the five-tube ac/dc complement as 100.

Tube Type	Initial Cost Index		*Probability of Replacement		†Replacement Cost Index	
35W4	14		0.0060		0.126	
50C5	23		0.0508		1.753	
12AV6	18		0.0130		0.351	
		55		0.0698		2.230
12BE6	23		0.0088		0.304	
12BA6	22		0.0117		0.386	
		45		0.0205		0.690
Totals		100		0.0903		2.920
Compactron		(Hypothetical)				
1.		44		0.0275		1.815
3.		43		0.0091		0.587
Totals		87		0.0366		2.402

* Per 1000 hours at maximum ratings.

† Based on annual use of 1500 hours.

This table shows that initial cost of the Compactron complement is less than the conventional tube complement, although each Compactron is estimated to cost nearly twice the highest tube price. The number of replacements of conventional tubes is 2.5 times as many as the Compactrons. Thus, the average replacement cost for Compactrons is less by about 17 per cent.

Since the Compactron is a recent development, only a limited amount of life test data have been generated. Our only "proof of the pudding" data to date have been obtained from life tests and field failures on four multifunction tubes to simulate the Compactron concept as follows:

Multifunction Tube Type	FR	Prototype Tubes Types	ΣFR	Ratio FR/ΣFR per cent
1. 6BW8	1.15	6CB6, 6AL5	3.49	33
2. 6CX8	2.55	12BY7, 6C4	3.79	67
3. 6T8	0.60	6C4, 6AL5	1.94	31
4. 6EZ8	0.88	12AT7, 6AB4	3.04	29
*2'. 6CX8	0.74	12BY7, 6C4	2.06	36

*Data from an equipment manufacturer's field failures.

Evidently it is possible for multifunction tubes to have failure rates as low as 30 per cent of their combined prototypes. Also, these ratios are in line with those previously estimated for Compactrons. We are convinced that the Compactron provides a major breakthrough in attaining higher reliability and lower cost.

Military System Reliability: Some Department of the Air Force Contributions

J. SPIEGEL†, Associate Member, IRE, and E. M. BENNETT†

Summary—This report discusses the evolution, since the formation of the Department of the Air Force in 1947, of the Air Force's administrative policy concerning the reliability of complex military electronic equipment and systems. It describes developments in defining and regulating the contractor reliability effort and the monitoring and advisory activity of the Air Force procuring agencies. By reference to numerous policy statements made by the Air Force, the report demonstrates that, within only a few years after its first stated concern regarding reliability, the Air Force has succeeded in developing a reliability program which is sufficiently detailed and integrated to provide substantial assurance of reliable equipment.

INTRODUCTION

The first paper[1] in this series on military system reliability discussed the evolution, from 1942 to the present, of the Department of Defense position concerning the reliability of complex military electronic equipment and systems. The present paper outlines the results of a parallel evolution within the Air Force establishment.[2]

Summary of DOD Activities[3]

For all practical purposes, the formation of the Vacuum Tube Development Committee (VTDC) marks the beginning of reliability efforts focused upon electronic equipment by the military services and the then War Department. When the war ended, the VTDC, having survived the organizational changes which took place during the war, was organized under the Joint Communications Board and in 1946 was transferred under the name of the Panel on Electron Tubes (PET) to the Joint Research and Development Board, which had been established four months previously.

In 1950, the Research and Development Board organized the Ad Hoc Group on Reliability of Electronic Equipment. This group stimulated the first definitive high-level policy statement concerning reliability when the Secretary of Defense, General George C. Marshall, indicated that every agency of the Department of Defense would be required to increase its emphasis upon the reliability of military electronic equipment.[4]

As one result of the issuance of the Ad Hoc Report in 1952, the Department of Defense organized a new and permanent group, the Advisory Group on Reliability of Electronic Equipment (AGREE). Subsequent to the organization of AGREE, the Panel on Electron Tubes (PET) was reorganized as the Advisory Group on Electron Tubes (AGET), and another group, the Advisory Group on Electron Parts (AGEP), was formed. AGREE, AGET and AGEP thus became the major groups concerned with the reliability of electronic equipment at the Department of Defense level.

In 1957, the Department of Defense formed an Ad Hoc Committee for Guided Missile Reliability (ACGMR). In contradistinction to the AGREE report, which was focused primarily on the technical aspects of reliability, the report of ACGMR, April, 1958, was directed toward the managerial aspects of reliability.

These ACGMR and AGREE reports, together with the newsletters and the other documents supplied by AGEP and AGET, provided the Department of Defense with a package program, managerial as well as technical, which theoretically would assist the military services in achieving and maintaining adequate reliability levels.

Department of the Air Force 1947-1959

Despite the fact that the earliest document clearly demonstrating official Department of the Air Force interest in reliability appeared in 1956, this interest may be assumed to have begun

---

† The MITRE Corp., Lexington, Mass.

[1] J. Spiegel and E. M. Bennett, "Military system reliability: Department of Defense contributions," IRE TRANS. ON RELIABILITY AND QUALITY CONTROL, vol. RQC-9, pp. 1-8; December, 1960.

[2] We personally owe much to the efforts of the many who supplied us with information and with leads to information. Particularly, we would like to thank F. L. Wenger of Headquarters, ARDC, Major H. Simon of Headquarters, USAF, R. C. Littler of Headquarters, AMC, and E. J. Lancaster of BMC.

[3] This material summarizes selected parts of our previous paper.

[4] "Reliability of Electronic Equipment," Dept. of Defense Directive No. 150.21-1; September 12, 1951.

earlier, as is evidenced by the reports on reliability published by "Project RAND" and other Air Force-sponsored agencies since the formation of the Department of the Air Force in 1947 and by the participation of the Department of the Air Force in the various committees and groups organized by the Department of Defense.

The first document specifically concerned with reliability and produced by an agency of the Department of the Air Force was Air Research and Development Command Regulation (ARDCR) 80-21, dated May 18, 1956, and titled "Reliability Considerations in the Research and Development of Electronic Equipment."[5] The purpose of this regulation was to prescribe ". . . the policy and . . . the responsibilities for implementation and accomplishment of reliability considerations in the research and development of electronic equipment." For the fulfillment of this purpose, the regulation established a requirement for greater specificity in noting technical factors such as shock, vibration and temperature which influence reliability. The regulation required that: "All specifications, exhibits, product descriptions, or other technical requirement documents will include as one of the major engineering factors, specific requirements for reliability. These requirements will be stated in quantitative terms consistent with the state-of-the-art and in consideration of other design factors. . . ."

Reports from the contractor were to state clearly and concisely what was being done to achieve the desired reliability, with the final report indicating the predicted reliability as well as other relevant information. The requirement in this regulation for specific, quantitative reliability statements in procurement documents, coupled with the requirement for reports from contractors of their efforts to achieve required reliability levels, thus provided the subcommands of ARDC with an initial managerial program for gaining and maintaining reliable equipments. A more recent publication, ARDCR 80-1, dated August 22, 1960, and titled "Reliability," will be reviewed in a later section of this paper.

On July 31, 1956, Air Materiel Command (AMC) issued its policy instructions with Headquarters Office Instruction (HOI) 100-3, "Communication—Electronics Reliability Committee," establishing an AMC Reliability Committee. The Committee, which drew its members from the Directorates of Maintenance Engineering, Procurement and Production, Plans and Programs, Supply, and Transportation and Services, as well as from the Quality Control Staff Office and ARDC elements, was assigned the responsibilities of 1) defining and relating problem areas of the proper agencies, 2) assisting in determining action to be taken in conjunction with the Department of Defense's AGREE working groups, and 3) providing reports to higher authorities. The committee members were given the authority to commit their respective directorates and staff offices to necessary actions which did not involve a policy deviation. HOI 100-3 has been replaced by Air Materiel Command Regulation (AMCR) 25-15, dated June 21, 1960, "Reliability Implementation and Monitoring Program for Weapon/Support Systems and Equipment." This AMCR will be reviewed in a later section of this paper.

As a direct result of ARDC Regulation 80-21, the Aeronautical Reconnaissance Laboratory (ARL) of Wright Air Development Division modified its procedures concerning formal contractual documents. Prior to this time, ARL had special reliability inserts placed in regular specifications. These inserts, one for the technical-development phase and one for the production phase, required reports from the contractor. However, with ARDC Regulation 80-21 making such reports a requirement, ARL felt that a formal contractual document should be promulgated in order to implement the ARDC policy.

Accordingly, on August 27, 1956, ARL started negotiations with the AMC legal and procurement staffs to evolve such a formal contractual document. On September 26, 1956, Exhibit WCLR 453 was produced.[6] In October, 1956, the Exhibit was revised, and by January 11, 1957, MIL-R-25717 (USAF), "Reliability Assurance Program for Electronic Equipment," replaced it to become the first of the specific United States Air Force military specifications concerned with electronic equipment reliability.[7] MIL-R-25717C (USAF),

[5] A regulation produced by a command element within the Department of the Air Force establishment is ". . . an official order . . . setting forth or prescribing rules, procedures, policies, or the like considered general in application and permanent in nature." This definition is taken from W. A. Heflin, Ed., "The United States Air Force Dictionary," Air University Press, p. 433; 1956.

[6] An Exhibit is a document that generally is attached to the request for bid and provides the bidder with information concerning some of the requirements he will face.

[7] Essentially, a military specification sets forth the requirements or standards for a piece of equipment, a material, a service to be performed, and the like. As indicated in the Dept. of the Air Force Manual 81-1, June 25, 1956, specifications are used ". . . to tell prospective bidders what the Government will buy, to set forth the minimum requirements that their process or commodity must meet, and to place them on an equal basis. With detailed specifications, interchangeability and

March 9, 1959, is the current version of the original, with little difference from that issued two years previously.

MIL-R-25717C (USAF) covers the general requirement for a reliability assurance program that the contractor must conduct for all pilot and production electronic equipment. The program must enable the contractor to achieve the reliability specified in the detail specifications. In achieving this figure, the contractor is cautioned not to assume that the production model will yield the same reliability as the prototype. Rather, he should, by using measures such as part failure rates and derating curves, compute ". . . the failure rate per part application and. . . estimate the expected reliability to be realized in his production." If the contractor finds that the expected reliability figure is lower than the required reliability, he is to take all necessary steps to improve the equipment. To aid the contractor in achieving the required reliability, the specifications list 12 areas that the contractor might find worth investigation. In addition, the regulation notes that the procuring activity will monitor the contractor's efforts by means of initial, special, and quarterly reports.

In April, 1958, the report of the Department of Defense's Ad Hoc Committee for Guided Missile Reliability (ACGMR), "Proposed Reliability Monitoring Program for Use in the Design, Development and Production of Guided-Missile Weapons Systems," published by the Department of Defense, was sent to Headquarters, USAF, which in turn sent it to AMC and ARDC Headquarters. The report was reviewed there for its applicability in the Department of the Air Force establishment and was then returned with comments to Headquarters, USAF on July 30, 1958.

Two months later, on June 2, 1958, the Communications and Navigation Laboratory, WADC, issued MIL-R-26484 (USAF), "Reliability Requirements for Development of Electronic Subsystems or Equipment," whose purpose was to detail ". . . the minimum requirements which must be followed by a contractor to assure the design of reliable equipment." The assurance results from requiring a complete reliability program to be devised by the contractor as well as requiring a quantitative and demonstrable mean-time-between-failure (MTBF). In the event that a MTBF is not specified in the detail-development exhibit or contract, MIL-R-26484 (USAF) establishes it as not less than 300 hours for airborne electronic subsystems. If the equipments are used individually, the MTBF may not be less than 500 hours. The specification also details how the contractor shall satisfy these requirements, and it suggests the efforts that the contractor might make for best results. For example, when the development equipments have been built, at least 50 per cent of them must be tested to demonstrate the achieved MTBF under specified environmental stresses. The particular techniques to be used are given in the specification, as are the formats for the formal report of results.

In the same month, on June 28, 1958, the Department of Defense, at the behest of the Navy and with the joint approval of the Air Force and Army, issued MIL-STD-441, "Reliability of Military Electronic Equipment." Almost immediately following the Department of the Air Force's concurrence on this Standard, Rome Air Development Center issued two implementing exhibits, Exhibit RADC-2629, October 31, 1958, "Reliability Requirements for Ground Electronic Equipment (Development and Service Test)" and Exhibit RADC-2693, November 25, 1958, "Reliability Requirements for Ground Electronic Equipment (Preproduction and Production)." The latter exhibit has recently been superseded by MIL-R-26474 (USAF), June 10, 1959, "Reliability Requirements for Production Ground Electronic Equipment."

MIL-STD-441, based upon the work of Task Group 4 of the Department of Defense's Advisory Group on Reliability of Electronic Equipment (AGREE) has as its purpose ". . . to establish a procedure for the development and design of electronic equipment to insure required inherent reliability." The established procedure was divided into two phases: first, study and planning; second, design and construction of prototypes. The first phase required that the contractor estimate the feasibility of design including the reliability and indicate any trade-off considerations in this very early stage of design. In MIL-STD-441 the distinction between "use" and "inherent equipment" reliability was made in order to assist the designer in his approach to reliability and to account for the factors of difference between the factory-tested "inherent" reliability and the final in-service operational reliability. This distinction is shown in Fig. 1.

Phase two of MIL-STD-441 is concerned with the actual design and fabrication of a prototype

---

standardization are insured in repeat purchases." There are different kinds of specifications, the content of each determining what class it falls into. For our purposes, the class of specifications we are interested in are "General Specifications," which deal with general requirements in a particular area. The requirement for reliability in all types of electronic equipment is clearly a characteristic which fits this category, and thus every specification which deals with reliability can be and is considered a general specification.

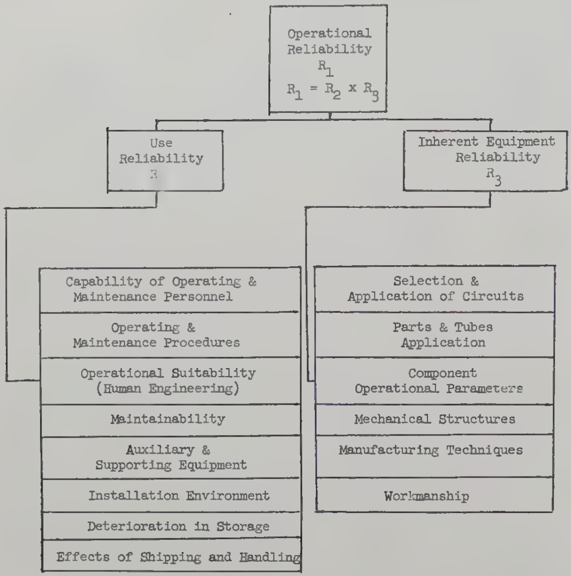


Fig. 1. A breakout of operational reliability.

model to meet the level of reliability estimated in phase one. Techniques for the control of debilitating environments are discussed. The final reports required of the contractor are exhaustive in nature. They must include, for example, "... an explanation of the procedures used to determine that parts have been suitably selected and applied. . . a description of circuit techniques employed to eliminate or minimize deleterious effects on equipment performance. . . an analysis of the evaluation tests . . . made to prove the equipment will have the required degree of reliability and maintainability."

The implementing document for ground electronic equipment, Exhibit RADC-2629, covers the "general reliability procedures and criteria for use during initial development of ground electronic equipment and details the minimum reliability requirements which the contractor must meet and demonstrate." The procedures are based upon the principle of "early and often" attention to reliability. For example, an estimate of the reliability of the total equipment is required ". . . not later than 30 days after contractor award." Every three months thereafter, the contractor has to refine this estimate in terms of the changes which have occurred in the design during the preceding period.

A basic formula is provided which specifies the minimum acceptable MTBF when the detailed equipment specifications do not so specify. The formula is:

MTBF (in hours) = $1/F_r$

where

$$F_r = 30\text{x}10^{-6}\text{x}N_t + 15\text{x}10^{-6}\text{x}N_m + 2\text{x}10^{-6}\text{x}N_s + 0.5\text{x}10^{-6}\text{x}N_c$$

N_t = total number of tubes (enveloped) included in the equipment parts complement

N_m = total number of motors and relays included in the equipment parts complement.

N_s = total number of semiconductors (transistors, diodes, etc.) included in the equipment parts complement.

N_c = total number of remaining electrical and electrical mechanical parts included in the equipment parts complement.

The Exhibit discusses the efforts that the contractor must expend to control thermal effects and requires him to design his circuits such that ". . . large deviations in circuit and component characteristics can be tolerated without degradation of performance below . . . an acceptable level." The contractor is further required to conduct such tests as are needed to demonstrate at " . . . an acceptable confidence level (90 per cent) that the required reliability has been provided." The criteria for accept-reject are tabled by MTBF multiples.

It should be noted that this document, Exhibit RADC-2629, and MIL-R-26484 (USAF) are milestones in that they constitute official Air Force statements requiring formal "accept-reject" testing before equipment acceptance by the procuring activity. This basic reliability concept is implemented by a quantitative level specified in terms of MTBF and a test to prove conformance or achievement of the level specified. It is, of course, one of the concepts developed in the AGREE report.

The companion Exhibit, RADC-2693, presents similar material, here concerned with production equipment. As noted above, the Exhibit has been superseded by MIL-R-26474 (USAF), effective June 10, 1959. However, there is little difference between the superseding and the original documents.

On March 23, 1959, Headquarters, USAF sent a letter to the Commanders of AMC and ARDC, stating, in part, that a real " . . . need for increased emphasis on reliability . . ." had arisen as a result of the increased complexity and costs of present weapon systems. As a result of this need, Headquarters, USAF, directed that " . . . all new weapon systems contracts include a meaningful reliability requirement . . ." and it proceeded to define "meaningful" by asserting that ". . . a contract should state clearly what the contractor is to achieve and, of equal importance, what specific tests or means the contractor must use to demonstrate achievement." The letter went on to deal with current contracts and contractors, making the point that these " . . . contractors should

be required to define present reliability goals and establish suitable tests to demonstrate that the reliability achieved meets operational needs." Although merely a letter to two subordinate commands, this letter is important in that it constitutes the first statement concerning reliability made by Headquarters, USAF.

A few days later, with a primary aim at aiding the quality control personnel, Headquarters, AMC issued AMC Pamphlet 74-1, March 31, 1959, "Reliability Evaluation Procedures for Pilot-Production and Production." This Pamphlet is basically " . . . a detailed explanation of the reliability index evaluation procedures recommended by Task Group Number 3 of the Advisory Group on Reliability of Electronic Equipment (AGREE). Specific emphasis is placed on methods for determining and evaluating the reliability index (mean-time-between-failure) of electronic equipment during pilot-production and production." Containing tabled and graphed figures of various functions such as "equipment reliability as a function of mission time and MTBF," "sequential sampling plan," and the like, the Pamphlet assists quality control persons to become relatively knowledgeable in these statistical evaluation techniques concerned with sampling for reliability evaluation.

This was followed a month later by Department of the Air Force Letter 84-1, April 30, 1959, subject, "Reliability Monitoring Program for Weapon Systems."[8] Attached to this letter was a modification prepared by representatives of both AMC and ARDC, of the Department of Defense's Ad Hoc Committee for Guided Missile Reliability (ACGMR) report. In this publication, directive in nature, the Department of the Air Force promulgated three rules: first, each contract must include a meaningful reliability requirement; second, the contractor must be prepared to submit to continuous monitoring of his reliability efforts; third, the contractor must prove that the established reliability requirements are satisfied through a formal series of acceptance tests.

Immediately following the issuance of the Department of the Air Force Letter 84-1, USAF Specification Bulletin 506, May 11, 1959, "Reliability Monitoring Program for Use in the Design, Development and Production of Air Weapon Systems and Support Systems," was published. This Specification Bulletin, also a modification of the ACGMR report, was a close copy of the attachment to Department of the Air Force Letter 84-1. With the publication of this Bulletin, procuring officers were provided with a document that could be used "externally," in contradistinction to Department of the Air Force Letter 84-1, which was an "internal" document.

After the publication of USAF Specification Bulletin 506, May 11, 1959, numerous reliability publications were issued in the following two-month period, most of them drawing upon the ACGMR and the AGREE reports. The day after "506" was produced, the first version of MIL-R-26667 (USAF), dated May 12, 1959, "Reliability and Longevity Requirements, Electronic Equipment General Specification For," was issued by the Directorate of Laboratories, Wright Air Development Center. On June 2, 1959, it was superseded by MIL-R-26667A (USAF). This specification " . . . covers the analysis and estimation of longevity, the method of measuring reliability and longevity, the analysis of deficiencies and report of effort to achieve specified reliability and longevity." To assist the contractor, the specification provides for a design analysis to be performed by the contractor in order to establish " . . . the failure rate for each part application and the expected reliability and longevity of the equipment." Repeated analyses are to be performed in order to account for " . . . effects on reliability and longevity which may occur because of changes in manufacture and supply." If variance does occur and the equipment is below the specified reliability, the contractor has to develop a plan which can raise the expected reliability to the required level. When referenced by a detail specification, the described analyses are added to contractual requirements and are considered part of the acceptance testing.

This general specification also outlines how reliability test environments should be established, how equipment for test should be selected, and how test procedures should be followed. In addition, it requires initial, special, prototype evaluation, progress, and part-failure-rate reports in order to provide the procuring activity with as much information as possible concerning reliability. MIL-R-26667A is an attempt to utilize the test plans of AGREE Task Groups 2 and 3.

On June 18, 1959, the Directorate of System Management, Headquarters, ARDC, issued MIL-R-26674 (USAF), "Reliability Requirements for Weapon Systems," whose purpose was to cover " . . . the general requirements for the establishment of an organized reliability program by the contractor to assure the attainment of the reliability requirements specified for the weapon system." The specification notes that this program

[8]An Air Force letter is administrative in nature and general in application. It contains " . . . regulatory material considered to be temporary in duration, or informative matter that may be of either temporary or permanent interest."

should take into account the efforts of subcontractors and vendors. The remainder of the document discusses those factors which can affect the reliability of equipment, factors such as "trade-offs," derating, redundancy, testing, and quality control. This particular specification, in combination with USAF Specification Bulletins 506 and 510, presents a complete program for a contractor to follow in establishing his reliability organization and program.

Shortly after this version of MIL-R-26674 was completed, the Air Research and Development Command released its May, 1959, Special Study Group report, "Reliability in Missile Programs." The Study Group, at the direction of the Commander, ARDC, was to investigate the problems associated with current missile reliability programs and develop recommendations for action by the Department of the Air Force to improve its program. When the study was completed, it was sent to 44 industrial and military organizations for comment and criticism; 35 responded in detail.

Soon after the special Study Group report was released, the Air Force Ballistic Missile Division, ARDC, and Ballistic Missile Center, AMC, issued a new exhibit pertaining to missile reliability. Designed specifically for ballistic missile systems, AFBM Exhibit 58-10, June 1, 1959, "Reliability Program for Ballistic Missile and Space Systems," provides " . . . optimum requirements and procedures for contractor reliability programs." The Exhibit requires that the contractor prepare a description of the reliability program that he intends to follow during the contractual period. His program must include a sequence of monitoring points which provide for time-phased reviews of reliability efforts and the results achieved by that program. These planned reviews will be made by the contractor as well as by the procuring agency. In order to assure that the specification's reliability requirements are met, the program must include provisions for considering reliability during the design stage. The reliability requirements are to be determined and demonstrated by the contractor. Major portions of the document are concerned with the details of the associated reporting system.

In order to provide "internal" direction, as contrasted with "external" direction as represented by MIL-R-26674 (USAF), the Directorate of System Management, ARDC, produced Directorate Office Instruction Number 57-3, June 23, 1959, "System Reliability." The Instruction established " . . . reliability policy, objectives, responsibilities, and procedures for system programs." Applying to all joint ARDC-AMC System Project Offices, the Instruction provides the project officers with procedures for system programs and a list of the officers' major responsibilities, among them:

1) Define and negotiate quantitative reliability requirements in contracts.
2) Require contractors to formulate and implement a comprehensive reliability program.
3) Establish and chair a system Reliability Review Board to monitor the program and results achieved.
4) Designate within the project office a Reliability Monitor.

In addition, a periodic review of each contractor's reliability efforts and results is to be performed by the "Reliability Review Board." This Board, organized as a subcommittee of the Weapon System Phasing Group, draws its members from the ARDC System Project Office, the AMC System Project Center, and the ARDC Test Center System Project Office, each supporting ARDC Development Center, the Logistics Support Manager, and the Operating Command. At the end of each review, the Board issues a report " . . . summarizing the status of reliability effort, results achieved, and any recommendations on design changes, reorientation of the program, funding, or other actions necessary to insure that the required reliability will be achieved." The Board may call upon technical advisors to guide it.

To provide a continuous effort, the Instruction further requires that one or more Reliability Monitors be appointed the following responsibilities:

1) Insuring that the provisions of this instruction and the reference documents are applied to programs in a timely fashion.
2) Exercising continuous surveillance of the contractor's reliability effort.
3) Providing the Systems Project Officer with the reliability factors that must be considered in all management decisions which can affect the operational reliability of the system.
4) Insuring that all available and applicable reliability methods, techniques, and criteria are employed by contractors and supporting Air Force activities.
5) Insuring that revisions to existing published procedures and criteria are applied to programs without undue delay including revisions to general specifications applicable to all programs.

Combined with ARDC Regulation 80-21, this Instruction completed, for the moment, the ARDC contribution to a formalized internal program. The Regulation provides the over-all policy; the Instruction tells how it will be managed and applied.

With the publication of U. S. Air Force Specification Bulletin Number 510, "Guides for Reliability Organization," on June 30, 1959, the managerial aspect of the Department of the Air Force reliability program was expanded further. This Bulletin was designed to aid contractors in establishing their reliability organization. The program required for the reliability organization is complex and varied and, in turn, requires a fine organizational setup. For the administration of the setup, the Bulletin presents three alternative means for determining the adequacy of a proposed reliability organization. The first is based upon the criteria developed by ARDC and AMC for their review efforts. The second is based upon the general experience acquired in numerous industrial programs. The third " . . . takes the form of a Master Check List of Reliability Program Practices based on a specific weapon system program and observation of similar programs."[9]

The next publication to appear was the Aeronautical Accessories Laboratory's MIL-R-27173 (USAF), July 6, 1959, "Reliability Requirements for Electronic Ground Checkout Equipment." This document was designed to detail " . . . the minimum requirements which must be followed by a contractor to assure the design and manufacture of reliable equipment." Like the other specifications, this specification covers the reports and requirements laid upon the contractor. A minimum MTBF is given (300 hours) to be used when the detail specifications do not provide an MTBF. Tests are required, as are reports similar to those required by preceding specifications.

On October 8, 1959, by means of Supplement 1 to Air Force Letter 84-1 of April 30, 1959, Headquarters, AMC implemented the letter and the purpose of the previous reliability documents. Each buying office was now required to:

1) . . . arrange for and conduct discussions, as necessary, with each participating contractor to establish agreement between contractor's programs and the Air Force reliability program criteria, and to identify any areas requiring increased emphasis. When the contractors' reliability programs are not consonant with Air Force criteria, request the contractors submit cost proposals for any additional work required and instruct them to be specific regarding the kind of activities and potential gains. Evaluate all cost proposals to determine the areas of activities in which increased effort is justified by the potential gains.
2) . . . hold contractors responsible for exploiting to the maximum extent possible, within the terms of the contract, the results of the review of programs and the principles and techniques of current reliability knowledge. The program proposals for work in areas requiring increased effort will be screened to determine the portions of the work covered and not covered by the terms of the present contract.
3) Obtain required program directive authority for the effort, which can be justified, through program direction channels from AMC . . . or ARDC as appropriate with required justification. If the AMC or ARDC cannot provide the required program, within current availability and/or flexibility, action will be taken by the responsible material program office (AMC/ARDC) to forward the fund requirement with required justification to Hq USAF. The required justification will make clear both potential over-all gain to the Air Force and the penalties for not taking necessary action in this area.
4) Insure that new contracts contain detailed descriptions of reliability program agreed upon by the Government and the contractor.
5) Insure that necessary action is initiated to contractually cover any changes in the contract requirements caused by the adoption of the revised reliability program or an initially defined reliability program for an existing contract.

One month later, upon ARDC receipt of industrial and military comments on and criticisms of the ARDC Special Study Group report of May, 1959, "Reliability in Missile Programs," these contributions and the original report were collated and 10 recommendations were published in ARDC Special Study Group, "A Study of Industry and Military Comments on Report 'Reliability in Missile Programs'," November 30, 1959. The recommendations are as follows:

1) The <u>Ballistic Missile Data Interchange System Program</u> now approved be carefully monitored and results observed for possible application to other missile areas.
2) Operations research methods be employed to determine completeness of data interchange requirements consistent with economic considerations.
3) A central authority be staffed for the coordination of the aims and objectives of the reliability programs within the Department of Defense and the Air Force.
4) Specific courses in reliability be established for personnel involved in management,

[9] This Master Check List was taken from the "Reliability Handbook, 7-58-2954-9," compiled by W. J. LeVan of Bell Aircraft Corp., Buffalo, N. Y.

design, fabrication, operation and maintenance of parts, components and systems. Reliability courses be established for briefing and study by professional technical societies and military technical seminars.

5) Environmental conditions encountered in space be defined and facilities capable of simulating these environments be developed.
6) Existing maintenance policies and directives be revised to incorporate the "remove and replace" concept. The maintenance and quality control techniques developed in the research and development phase of the system be carried over into the operational phase.
7) The principles of mathematical methodology be compiled for wide distribution within the missile industry.
8) Mathematical techniques be developed and improved for determination of random failure occurrences in small samples.
9) Air Force implement and provide the necessary management and manpower spaces to prepare up-to-date procurement specifications, extend control over subcontractors and vendors material, and process quality and include adequate and realistic reliability requirements.
10) Adequate support for research be established on materials, processes, and component parts, including basic physical and chemical properties of materials, mechanisms of failure of parts and assemblies.

The Ballistic Missile Data Interchange System Program, noted in the first of these recommendations, was officially established by the Air Force (AFBMD and BMC) together with the Army (ABMA) and Navy (BUORD), as the "Interservice Data Exchange Program" (IDEP). The program is designed to provide an interchange of data resulting from tests of ballistic-missile components and parts. The results of these tests are to be sent to a "Data Distributing Center" (DDC) whose function it is to reproduce the reports and distribute them to the member contractors. To date, three joint-services procedures have been released, all during January, 1960. These are: IDEP-I, "Procedures for Participants"; IDEP-II, "Codes for Establishing Index Numbers"; IDEP-III, "General Procedure for Data Distribution Centers."

On June 21, 1960, AMC HOI 100-3, July 31, 1956, was replaced by AMC Regulation (AMCR) 25-15, "Reliability Implementation and Monitoring Program for Weapon/Support Systems and Equipment."[10] In many ways the regulation provided a major step forward in reliability monitoring for AMC. The primary purpose of this regulation was to " . . . insure a high level of operational reliability in Air Force materiel." This assurance came about through the establishment of an AMC Reliability Coordinator, who was to serve in three ways:

a) Establish AMC policy and procedures to insure that weapon/support systems and equipment reliability standards conform with approved operational requirements.
b) Coordinate with the Air Research and Development Command on reliability policies and procedures.
c) Serve as the focal contact point for agencies outside this Command on matters concerning reliability.

In addition, the Directorates of Procurement and Production, Supply, Maintenance Engineering, and Transportation of Headquarters, AMC were given specific responsibilities within their own areas. AMC Centers were charged to:

a) Insure that complete and realistic reliability requirements are incorporated in contracts and that necessary reliability-data collection, reduction, feedback and corrective action, as well as an adequate reliability monitoring program, are specified in appropriate contracts.
b) Insure that consideration is given to reliability requirements and capabilities by source selection boards.
c) Review contractors' reliability programs to insure that all essential actions related to reliability are being pursued in an organized manner by each contractor.
d) Designate a reliability coordinator and an alternate to serve as the reliability focal point for the Center, and report by letter the names of the designees to the Hq AMC Reliability Coordinator (MCPE).
e) Designate a reliability monitor and an alternate in each project office to serve as reliability focal point for the office, and report by letter the names of the designees to the center reliability coordinator.

Air Materiel Areas and Depots were instructed to aid in this program by compiling the necessary reliability data by including a reliability program in the logistic plans, and in other ways.

---

[10] AMCR 25-15 was superseded on February 15, 1961, by AMC Supplement No. 1 to AFR 375-5. This change will be discussed later in the paper.

This AMC regulation laid down the conditions under which AMC sought to obtain highly reliable equipment from its contractors. Of course, AMC, in general, was not charged with the responsibility of research and development, and, therefore, its contribution in the initial stages of system development was through the Air Research and Development Command (ARDC).

On August 22, 1960, ARDC issued ARDCR 80-1, "Reliability." This new regulation, which, incidentally, does not rescind ARDCR 80-21, prescribes " . . . ARDC policy, assigns responsibilities, and establishes procedures for attaining reliability during research and development." The regulation defines ARDC responsibility as threefold:

a) All reliability development including research, design, development testing, definition of detailed engineering requirements for reliability, managing systems reliability programs, providing technical guidance to the program, and evaluating and validating results.

b) Conducting research on the nature of the problem to improve understanding of the basic theories of reliability.

c) Development of general reliability techniques.

In order to assume these responsibilities, ARDC established its policy as requiring that the ". . . techniques of systems analysis and operations research will be applied . . . to define reliability requirements which will optimize the system . . . ;" specific minimum acceptable reliability requirements will be included in all contractual documents; a " . . . comprehensive and organized contractor reliability program . . ." will be included in all contractual documents; test plans for demonstration of achieved reliability, as well as for failure analysis, will be incorporated in contractual documents; " . . . reliability will be a major factor in all source selection actions . . ."; new programs will make provisions for funds to be used in reliability efforts; and a reliability research program will be established and funded by ARDC. Thus, it is evident that ARDC intends to go to great lengths in order to obtain the reliability it feels is required.

The various ARDC development divisions are charged with implementing these policy statements. In addition, the three major divisions are assigned the following area responsibilities " . . . for compiling and maintaining a central source of information for activities in the assigned area, within ARDC, other government services, and private industry . . . :"

a) Wright Air Development Division—design for reliability to include systems analysis techniques, design techniques, prediction techniques (non-electric), and others.

b) Command and Control Development Division—analysis and measurement to include statistical methods, small sample testing, accelerated aging testing, etc.

c) Ballistic Missile Division—control for reliability to include reliability management controls, requirements for reliability in contractual documents, training, etc.

Various procedures are outlined by which system offices will follow this regulation. Altogether, this is probably the clearest and most concise statement of reliability aims, policies, and goals that has recently been published. If the regulation has the same effect in application that it has in theory, many of the major organizational problems facing today's contractors, theorists, engineers, and military buying offices should be resolved in the near future. In any event, this is a major step.

Soon after ARDCR 80-1 had been published, the Air Force issued AFR 375-5, "Reliability Program for Weapon, Support and Command and Control Systems," dated October 17, 1960. This regulation too is indicative of the major steps which have been taken in the reliability area since the early Air Force days. Because Air Force contracts are so important to the industrial manager, the policy for the Air Force reliability program is quoted here in its entirety.

a) Reliability is considered a fundamental characteristic of every part, component, module, and complete system.
   1) Reliability will be stressed during early system studies, source selection, design, development and production.
   2) Maintenance, storage, transportation, and operation activities should exercise appropriate controls to maintain the reliability of the delivered article.
   3) Systems in development and production and future systems will be analyzed, and an appropriate reliability program with realistic requirements will be established for each. Each program will include numerical probability values from a minimum acceptable to the desired goal, with such intermediate quantitative values required to measure progression, and a stated minimum acceptable confidence level for each probability value.

b) Specifications, exhibits, and product descriptions and contracts for systems and associated materiel, including GFE for inventory, will include specific minimum acceptable reliability requirements as one of the major engineering factors.

c) Contracts for systems and major subsystems will include a requirement for a comprehensive contractor reliability program.
d) The Air Force will maintain surveillance during all phases of development and production over the contractor's reliability program, his reliability testing, and quality control activities. Collaboration by reliability, production, and quality control personnel with engineering personnel during concurrent development and production will not relieve the engineering agencies of the responsibility for engineering approval.
e) Contractors' reliability capability, both past performance and proposed programs, will be a major factor in all source selection action.
f) If contract reliability requirements are not met, or if the contractors' reliability effort is decreased, the decision to accept or reject the end item or the revised reliability program will be considered with a view toward monetary penalties, unit price decreases, or other considerations deemed equitable.
g) The adequacy of planned reliability efforts, including funds availability, shall be considered when reviewing new programs. Proposals for increasing reliability efforts and funds on programs in existence shall be considered on the basis of the net effect on the over-all Air Force capability and economy, including such factors as spare parts requirements, maintenance workloads, engineering changes, operating costs, and the effect on the system concerned.
h) Reliability monitoring points will be generally established in the following sequence:
   1) Detailed design study.
   2) Preprototype.
   3) Prototype.
   4) Preproduction demonstration.
   5) Demonstration of service readiness.
   6) Service evaluation.
   7) Full-scale production.
   8) Demonstration of major product improvement.

   However, this generalization is not intended to delineate the complete or ideal system cycle, but to emphasize the typical points at which the program should be monitored.

Paragraph f) should be particularly perused, since this indicates the first time that monetary or other penalties for failure to meet reliability goals have been officially sanctioned by the Air Force. The various Air Force subordinate commands are assigned the responsibility of actually carrying through these policies.

On February 15, 1961, AMC superseded their regulation 25-15 with a supplement to AFR 375-5. This supplement is almost an exact copy of their original regulation with only minor changes and does not indicate any change in their policy of strongly emphasizing the contribution of reliability factors to general system design and production.

To summarize the foregoing, one should peruse Table I, which presents a rather quick view of relevant current Air Force documents. With the recent reorganization of the Air Force soon to be an established fact, many of the documents cited might be superseded. Certainly there is a tendency to combine these requirements into one or a few documents. The degree of success of such a move remains to be seen.

The foregoing discussion describes the growth of an idea or policy within one governmental agency. Surely the same growth cycle can be seen in other military establishments. Although it has been only eight to ten years since the Air Force first realized that reliability of electronic equipment is of primary concern, its documentary program is now highly developed. Contractors are at last required, as are the Air Force buying agencies, to assure reliable equipment. The time may well come when reliability problems will present only minor difficulties.

TABLE I

SUMMARY TABLE OF CURRENT RELIABILITY DOCUMENTS

Document	Internal USAF	General	Ground Electronic Equipment	Airborne Electronic Equipment	Ballistic Missiles	Remarks
AFR 375-5	x					Establishes general AF reliability policy.
AMC Supp. 1 to AFR 375-5	x					Establishes additional AMC policy.
ARDCR 80-1	x					Establishes ARDC policy.
ARDCR 80-21	x					Provides earlier version of ARDC policy.
MIL-R-25717C (USAF)		x				General requirements for reliability assurance program.
MIL-R-26484 (USAF)				x		Minimum requirements for design.
MIL-STD-441		x				Reliability procedures for development and design.
RADC Exhibit 2629			x			Reliability procedures and criteria for equipment in development.
MIL-R-26474 (USAF)			x			Reliability procedures and criteria for equipment in production.
AMC Pamphlet 74-1		x				Reliability index evaluation procedures.
USAF Spec. Bulletin 506		x				Reliability monitoring program.
MIL-R-26667A (USAF)		x				Measurement of reliability and longevity.
MIL-R-26674 (USAF)		x				General requirements for reliability program for weapon systems.
USAF Spec. Bulletin 510		x				Evaluation of contractor programs.
AFBM Exhibit 58-10					x	Reliability monitoring program.
ARDC, DSM, DOI 57-3	x					Establishes SPO responsibilities and procedures for reliability.
MIL-R-27173 (USAF)				x		Electronic ground checkout equipment.
AFBM IDEP Program		x				Sets up data interchange program.

Letters to the Editor

In a recent article,[1] I find the author's formulation of the problem unsatisfactory, and his calculations incorrect for the redundant machine case (i.e., $N \geq 2$). Markov chain theory yields a simple solution to his problem without making his initial assumption that at the beginning of the use-maintenance cycle all equipments are working. The steady-state solutions of the Markov chain are, in my estimation, the real availability of the equipment in question; the values obtained by Bielka, which appear to be incorrect, are a conditional availability which can easily be obtained from the transition matrix which determines the Markov chain.

Bielka talks about a use-maintenance cycle divided into three fixed time periods:

t_1 = the use or mission time for the equipment during which no maintenance can be performed even if the equipment is redundant.

t_z = the maintenance time available to repair the equipment provided it needs maintenance following the use period. (During this period, it is assumed the equipment cannot fail).

t_s = the set up time for maintenance. (During this period, it is assumed that equipment cannot fail).

While in the redundant case of N equipments in parallel, it is only necessary for one of them to work, Bielka makes the assumption that the equipment is not available at the start of the next mission unless all N equipments are working as he assumes they are initially. Actually, this may be a good assumption to make if considered in connection with the reliability desired over the mission time, but I will not make it here. I will assume the equipment is available if at least one of N is working. Then if

$R = R(t_1)$ = the probability one equipment works during use time t_1,

$M = M(t_z)$ = the probability of finishing repair during maintenance time t_z,

I will say (using Bielka's initial condition) the equipment is available at the start of the next use time with probability $1 - (1-R)^N(1-M)^N$. This value also can be obtained from the transition matrix of the Markov chain to be given below.

In most of the examples I work out here, I make the assumption that even if no equipment is available that maintenance stops during t_1, and t_s must be repeated after t_1. (An example of this would be nonessential piece equipment on a scheduled airliner where maintenance can only be done on the ground). I also make the assumption that maintenance can be performed separately on each failed piece of equipment, i.e., there is one repair facility available for each failure that occurs during the use cycle. Bielka refers in his paper to the case where there is only one repair facility to handle all failures that occur. If this is so, then the results I obtain will be higher than the true situation and I will explain how to correct this and another possible unrealistic assumption at the end of this letter.

Let us first of all see where Mr. Bielka is incorrect in his calculation. He says the availability "is affected by two probabilities.

1) Probability of not requiring maintenance, or maintenance reliability.
2) Probability of maintenance being completed, assuming it was necessary, or maintainability."

The error is in 2) since his maintainability M, is for only one piece of equipment. If more than one fails then his definition is wrong. Using my assumption above, if i equipments fail, $(i = 1, \ldots, N)$, then the maintainability is M^i. Also since the probability of exactly i failing is $\binom{N}{i}(1-R)^i R^{N-i}$, we see under Bielka's initial condition that all units work:

$$\text{Availability} = \sum_{i=0}^{N} P\left\{\begin{matrix}\text{i units}\\ \text{fail in } t_1\end{matrix}\right\} \cdot P\left\{\begin{matrix}\text{i units}\\ \text{repaired}\\ \text{in } t_z.\end{matrix}\right\}$$
$$= \sum_{i=0}^{N} \binom{N}{i} (1-R)^i R^{N-i} M^i.$$

This equation only agrees with Bielka's definition for N=1, i.e., A=M (1-R) + R. This result occurs because in general it is not true that $P\{1 \text{ or more failures in } t_1\}, P\{\text{repair 1 failure in } t_z\} = \sum_{i=1}^{N}$

[1] R. P. Bielka, "Availability—a system function," IRE TRANS. ON RELIABILITY AND QUALITY CONTROL, vol. RQC-9, pp. 38-42; September, 1960.

$P\{i \text{ failures in } t_1\}\ P\{\text{repair } i \text{ failures in } t_z\}$. What we obtain from Bielka's error is an over estimate of the availability. In cases where two or more failures are highly unlikely, then Bielka's answer affords a good approximation to the correct value (but the error is on the positive side, and I believe it would be better if we had a negative error). In due respect to the author, I feel I should mention that I have found others who have made this mistake in probability calculations also. If we examine the answers one obtains in examples A to F of Bielka's paper, we see that mine are always smaller except if N = 1.

No.	Example	Bielka's Availability	Dick's Availability
1	A	0.855	0.855
2	B	0.768	0.732
3	C	0.715	0.626
1	D	0.943	0.943
2	E	0.908	0.896
3	F	0.887	0.849

Finally, let us look at the Markov chain approach. Let

p_{jk} = the probability that k out of N units will work at the start of the next mission given that j out of N were working at the start of the present mission.

Then for the model proposed above

$$p_{jk} = \sum_{i=o}^{\min[k,\,j]} \binom{j}{i} R^i (1-R)^{j-i} \binom{N-i}{k-i} M^{k-i}$$

$(1-M)^{M-k}$, j and k = 0, . . . , N.

By interchanging the order of summation of i and k, it can be easily shown that:

$$\sum_{k=0}^{N} p_{jk} = 1.$$

The transition matrix of the Markov Chain is

$$P = \left[p_{jk}\right].$$

The steady-state equations of the chain are

$$X_k = \sum_{j=0}^{N} p_{jk}\, X j,\ k = 0, \ldots, N \text{ and}$$

$$\sum_{k=0}^{N} X_k = 1.$$

The interpretation of X_k is the average proportion of use cycles starting with k working equipments (after a sufficient period of operation so that the initial state has little influence). I would define the availability of my equipment as

$$\sum_{k=1}^{N} X_k = 1 - X_o.$$

(Bielka's logical definition from what he wrote in his paper could be: availability = X_N).

Examples

I will solve formally the case N = 1 and given the numerical results for cases A, B and C of Bielka's paper.

N = 1

$$P = \begin{bmatrix} 1 - M & M \\ (1-R)\,(1-M) & R + M\ (1-R) \end{bmatrix}.$$

The steady-state equations are

$$X_o = (1-M)\,X_o + (1-R)\,(1-M)\,X_1$$

$$X_1 = M\,X_o + [R + M(1 = R)]\,X_1$$

$$X_o + X_1 = 1.$$

$$\text{Then } X_o = \frac{(1-M)\,(1-R)}{1-(R)\,(1-M)}$$

$$X_1 = \frac{M}{1-(R)\,(1-M)}.$$

Notice $p_{11} = R + M\,(1-R)$ is Bielka's availability as given in his paper. This probability is conditional on starting in state 1. My definition would be X_1 for availability of the system.

Definition: The reliability of a system during time t_1 is:

$$W = W(t_1) = \sum_{k=1}^{N} X_k\ [1-(1-R)^k].$$

For example, A in Bielka's paper
R = 0.606
M = 0.633.

$$\text{Hence } P = \begin{bmatrix} 0.367 & 0.633 \\ 0.145 & 0.855 \end{bmatrix}$$

$X_o = 0.186$, $X_1 = 0.814$
W = 0.493, so that the unit here completes less than half of all missions scheduled.

For N = 2

$$p = \begin{bmatrix} (1-M)^2 & 2(1-M)M & M^2 \\ (1-R)(1-M)^2 & (1-M)[R+2M(1-R)] & M[R+M(1-R)] \\ (1-R)^2(1-M)^2 & 2(1-R)(1-M)[R+M(1-R)] & (1-R)^2M^2+2(R)(1-R)M+R^2 \end{bmatrix}.$$

In my corresponding Example B

$$P = \begin{bmatrix} 0.135 & 0.464 & 0.401 \\ 0.053 & 0.405 & 0.542 \\ 0.021 & 0.247 & 0.732 \end{bmatrix}.$$

If both equipments are up, the availability is 0.247 + 0.732 = 0.979. If one is now up and the other down, the availability is 0.405 + 0.542 = 0.947. If both equipments are down, the availability is 0.464 + 0.401 = 0.865.

Bielka's definition would be availability = 0.732 since he assumes both equipments are now working. (The reason he gets 0.768 is due to the error in calculation mentioned above).

Here $X_o = 0.035$, $X_1 = 0.303$, $X_2 = 0.662$.
$W = 0.743$.

For $N = 3$, the corresponding Example C is

$$P = \begin{bmatrix} 0.049 & 0.256 & 0.441 & 0.254 \\ 0.020 & 0.182 & 0.455 & 0.343 \\ 0.008 & 0.108 & 0.425 & 0.463 \\ 0.003 & 0.054 & 0.317 & 0.626 \end{bmatrix}$$

$X_o = 0.007$, $X_1 = 0.085$
$X_2 = 0.369$, $X_3 = 0.539$
$W = 0.869$.

As promised above, I would like to show how to make the assumptions more realistic. In the case where at the start of a mission there are no equipments working, it will mean that there is no use period on that cycle, and we now assume maintenance can continue uninterrupted. Hence the maintenance period for this case is not t_z but $t_1 + t_z + t_s$. In Example A, given that state 0 holds, we have $M(t_1 + t_z + t_s) = 1 - e^{-\mu(t_1 + t_z + t_s)}$ or since $t_1 = 10$, $t_z = 4$, $t_s = 1.5$, $\mu = 0.25$, $M(15.5) = 0.979$.

$$P = \begin{bmatrix} 0.021 & 0.979 \\ 0.145 & 0.855 \end{bmatrix}.$$

(Notice the last row is unchanged.)

In this case $X_1 = 0.871$ which is higher than 0.855, the probability that a working unit works at the next use cycle. The reason for this is that now a failured unit is almost certain to be repaired over time $t_1 + 2t_z + t_s$, and hence the weighted average of both states exceeds 0.855, i.e., the unconditioned availability here is greater than Bielka's conditional formula predicts. Also W = 0.528.

How to correct the zero state in other cases ($N > 1$) is now quite clear. Reliability wise, it appears it might be best not to permit the use of the equipment until at least k (greater than 1) out of N units are up even though one can work the system with 1 unit working. This question, however, I leave to another study.

The problem of how to handle the maintenance case of only one facility handling i units in time t_z is that of finding the probability $\sum_{1=o}^{2} X_j \leq t_z$ where X_j is the time for one repair. In the exponential case this would be:

$$P\{i \text{ repairs in time } t_z\} = e^{-(\mu t_z)} \frac{(\mu t_z)^i}{i!}.$$

If we let

$$M_k = 1 - \sum_{i=o}^{k-1} e^{-(\mu t_z)} \frac{(\mu t_z)^i}{i!},\ k = (, \ldots \infty,$$

or in general

$$M_k = 1 - \sum_{i=0}^{k-1} P\{\text{repairing } i \text{ errors in } t_z.\}$$

$= P_1\{\text{Repairing at least k units in time } t_z\}$.
Note $M_o = 1$.

Then the availability is under Bielka's assumption:

$$A = \sum_{i=0}^{N} \binom{N}{i} (1-R)^i R^{n-i} Mi.$$

For case A, the result is unchanged, but in cases B and C we obtain:
$A_B = 0.711$, $A_C = 0.577$.
This last modification can also be put into the Markov chain formula.

Nevertheless, Mr. Bielka's paper as it stands is only useful and correct for the case N = 1 and some comment by your journal is appropriate.

Ronald S. Dick
International Electric Corp.
Paramus, N. J.

Authors Reply

My initial impulse upon reading Mr. Dick's letter was to discard it. . . . However, I asked one of our mathematicians to review his comments, such as they were, and ascertain their validity.

His statements of my assumptions are essentially correct. I assumed that all equipments must be working at the start of the next mission. If it were not necessary, there would be no need for redundancy. Dick's comments apparently assume that only one piece of equipment can be repaired at one time; I have assumed that work is begun simultaneously on all failures. . . . , there is indeed useful information in his letter.

Contributors

Donald C. Berman (A'57 - M'58) majored in electrical engineering at the Carnegie Institute of Technology, Pittsburgh, Pa., and in industrial management at New York University, where he received the B. S. degree.

He was employed as Manager of Engineering Quality Control at the Polarad Electronics Corporation and as Head of the Reliability Assurance Department, Olympic Division, of the Siegler Corporation. He is presently Senior Reliability Engineer in the Fairchild Astrionics Division, Fairchild Engine and Airplane Corporation, Wyandanch, L. I., N. Y., where he has reliability and quality control responsibilities in the AN/USD-5 High Endurance Surveillance System which Fairchild is developing for the U. S. Army Signal Corps, in addition to similar responsibilities in other projects.

Mr. Berman is a member of ARS, AOA, and ASQC.

J. Alfred Davies received the B.A. degree in chemistry (with a minor in physics) and the M.A. degree in mathematics from the University of Alabama, where he was a recipient of the Comer Award for Advanced Mathematics. He has also done other postgraduate work in statistics toward the Doctorate at Mississippi State College.

He was an Instructor in mathematics at the Engineering School, University of Alabama, and Mississippi State College prior to joining Ken-Rad Tube and Lamp Company (presently Owensboro Tube Plant, General Electric Company). He worked in various capacities as a design engineer and product engineer for his first three years with GE. For eight years, he was associated with quality control activities at the Owensboro Tube Plant. He was Supervisor of the Statistical Control Methods Section for the Receiving Tube Department for four years. He is presently Manager of the Statistical Engineering Section, Receiving Tube Department. Among his other achievements, he developed the variables sampling plan used in military and GE specifications for electron tubes. He is also Professor of elementary, advanced, and applied statistics at Kentucky Wesleyan College, Owensboro.

Mr. Davies is a Fellow of the ASQC and a member of Sigma Xi. He is also Chairman of the JT-11 Committee on Sampling Procedures of the Electronic Industries Association.

Nicholas E. Golovin was born in Odessa, Russia, and came to the U. S. in 1923. He received undergraduate and graduate degrees in mathematics and mathematical physics from Columbia College and University, New York, N. Y., and the Ph.D. degree in theoretical physics from George Washington University, Washington, D.C., in 1955.

He was a Research Statistician with R. H. Macy & Company for eight years. In 1943, he entered Government service as Chief, Production and Requirements Analysis Section, Tools Division, U. S War Production Board. From 1944 to 1946, he served as an Officer in the U. S. Navy with the Bureau of Ordnance, Office of Strategic Services and the NRL. He became Associate Superintendent of the Electricity Division at NRL in 1947, and, in 1948, Chief of the Management Planning Staff at the Naval Ordnance Test Station, Inyokern, Calif., where, from 1949 to 1958, he was Executive Assistant to the Director, Associate Director for Administration, and Associate Director for Planning. In March, 1958, he became Chief Scientist at the White Sands Missile Range, N. M. He became Director of the Technical Operations Division and Deputy Chief Scientist of ARPA in February, 1959, and September, 1959, respectively.

He is presently Vice President and General Manager of Rabinow Engineering Company, Inc., Washington, D. C., where he has been since August, 1960. He also serves as Consultant to the Associate Administrator of NASA in reliability and related matters.

Dr. Golovin is a member of the American Physical Society, American Nuclear Society, ARS, AAAS, Philosophical Society of Washington, and the AOA.

H. Leslie Hoffman (SM'57), founder and President of Hoffman Electronics Corporation, Los Angeles, Calif., keynoted the Seventh National Symposium on Reliability and Quality Control, held in Philadelphia, Pa., January 9 - 11, 1961.

Mr. Hoffman is a prominent representative of the electronic industry. A pioneer in the field, he built his own company from a small radio manufacturing business with a handful of employees, in 1941, to a leading national company in consumer, military and industrial electronics, with 4000 employees. He was recipient of the Electronic Industry Association Man of the Year Award in 1958, and in 1959 received the Western Electronic Manufacturer's Medal of Achievement.

Samuel N. Lehr (SM'58) received the B. S. degree from the College of the City of New York and the M. S. degree in nuclear engineering from the University of Cincinnati, Ohio.

He has had 20 years of experience in the development of nuclear reactor controls; design and development of distribution transformers and feeder voltage regulators; quality control on naval gun-directing systems; monitoring reliability programs of associated contractors on missile systems; estimating and predicting control and guidance system reliability and reliability trends; and determination of effects of environments (including long-term and pulsed radiation) on electrical and electronic equipment. He is presently with Space Technology Laboratories, Los Angeles, Calif.

Mr. Lehr is a member of the American Institute of Nuclear Engineers and the National Society of Professional Engineers.

Christopher D. McCool (M'53-SM'56) was bo in Bridgeville, Pa., on October 28, 1918. He received the B.S.M.E. degree from the Carnegie Institute of Technology, Pittsburgh, Pa., in 1940.

He worked for a short time with the Ken-Rad Tube and Lamp Corporation as a manufacturing engineer prior to World War II. After serving in the Corps of Engineers and as a Communications Officer in the USAF, he joined the General Electr Company's Receiving Tube Department in 1946. He worked as a manufacturing engineer until 194 at which time he transferred to the Design Engineering Section at Schenectady, N. Y. He is presently Manager of Entertainment Products Design General Electric's Receiving Tube Engineering Section at Owensboro, Ky.

V. J. Tronolone received the B. S. degree from the University of Arizona, Tucson.

His ten years of experience includes work in chemical engineering research, petroleum production research and development, chemical milling, and missile and space vehicle materials. He is presently with Space Technology Laboratories, Los Angeles, Calif., where he has performed Systems Engineering/Technical Direction activities on Atlas and Minuteman weapon systems, has been responsible for a foam study program, and has worked on the selection of materials for payloads of the Able series, and for the new Orbiting Geophysical Observatory. He holds three patents.

Mr. Tronolone is a member of the American Chemical Society.

INSTITUTIONAL LISTINGS

The IRE Professional Group on Reliability and Quality Control is grateful for the assistance given by the firm listed below and invites application for Institutional Listings from other firms interested in the field of Reliability and Quality Control.

BERNARD HECHT AND ASSOCIATES, 5455 Wilshire Blvd., Los Angeles 36, Calif.
Reliability and Quality Control Consultants; Reliability Training and Recruitment

The charge for an Institutional Listing is $20 for one or $25 for two consecutive Listings. Applications for Institutional Listings and checks (made payable to The Institute of Radio Engineers, Inc.) should be sent to L. G. Cumming, Professional Groups Secretary, Institute of Radio Engineers, 1 East 79 Street, New York 21, N. Y.